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(54) METHODS FOR OLIGOMERIZING OLEFINS

VERFAHREN ZUR OLIGOMERISATION VON OLEFINEN

PROCEDES POUR OLIGOMERISER DES OLEFINES

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Description**PRIORITY CLAIM**

5 **[0001]** This application claims the benefit of and priority to US provisional application USSN 60/660,018, filed March 9, 2005.

FIELD OF THE INVENTION

10 **[0002]** This invention relates to the selective oligomerization (specifically trimerization and/or tetramerization) of olefins (specifically ethylene) using catalysts.

BACKGROUND OF THE INVENTION

15 **[0003]** The oligomerization of ethylene typically returns a broad distribution of 1-olefins having an even number of carbon atoms (C₄, C₆, C₈, C₁₀, etc.). These products range in commercial value, of which 1-hexene may be the most useful, as it is a comonomer commonly used in the production of commercial ethylene based copolymers.

[0004] Several catalysts useful for the oligomerization of olefin monomers have been developed, including the trimerization of ethylene. Several of these catalysts use chromium as a metal center. For example, U.S. Pat. No. 4,668,838, assigned to Union Carbide Chemicals and Plastics Technology Corporation, discloses a chromium catalyst complex formed by contacting a chromium compound with hydrolyzed hydrocarbyl aluminum and a donor ligand such as hydrocarbyl isonitriles, amines, and ethers. U.S. Pat. No. 5,137,994 discloses a chromium catalyst formed by the reaction products of bis-triarylsilyl chromates and trihydrocarbylaluminum compounds.

20 **[0005]** U.S. Pat. No. 5,198,563 and related patents, issued to Phillips Petroleum Company, disclose chromium-containing catalysts containing monodentate amide ligands. A chromium catalyst complex formed by contacting an aluminum alkyl or a halogenated aluminum alkyl and a pyrrole-containing compound prior to contacting with a chromium containing compound is disclosed in U.S. Pat. Nos. 5,382,738, 5,438,027, 5,523,507, 5,543,375, and 5,856,257. Similar catalyst complexes are also disclosed in EP0416304B1, EP0608447B1, EP0780353B1, and CA2087578.

25 **[0006]** Several patents assigned to Mitsubishi Chemicals also disclose chromium catalyst complexes formed from a chromium compound, a pyrrole ring-containing compound, an aluminum alkyl, and a halide containing compound, including U.S. Pat. Nos. 5,491,272, 5,750,817, and 6,133,495. Other catalyst complexes are formed by contacting a chromium compound with a nitrogen containing compound such as a primary or secondary amine, amide, or imide, and an aluminum alkyl, as disclosed in U.S. Pat. Nos. 5,750,816, 5,856,612, and 5,910,619.

30 **[0007]** EP0537609 discloses a chromium complex containing a coordinating polydentate ligand and an alumoxane. Similarly, CA2115639 discloses a polydentate phosphine ligand.

35 **[0008]** EP0614865B1, issued to Sumitomo Chemical Co., Ltd., discloses a catalyst prepared by dissolving a chromium compound, a heterocyclic compound having a pyrrole ring or an imidazole ring, and an aluminum compound. EP0699648B1 discloses a catalyst obtained by contacting chromium containing compound with a di- or tri-alkyl aluminum hydride, a pyrrole compound or a derivative thereof, and a group 13 (III B) halogen compound.

40 **[0009]** WO03/053890, and McGuinness et al., J. Am. Chem. Soc. 125, 5272-5273, (2003), disclose a chromium complex of tridentate phosphine ligands and methylalumoxane (MAO) cocatalyst. However, due to serious drawbacks in the preparation of the phosphine-containing system, the use of a thioether donor group to replace the phosphorus donor in the ligands was also investigated.

45 **[0010]** WO02/083306A2 discloses a catalyst formed from a chromium source, a substituted phenol, and an organoaluminum compound. WO03/004158A2 discloses a catalyst system which includes a chromium source and a ligand comprising a substituted five membered carbocyclic ring or similar derivatives.

[0011] U.S. Pat. No. 5,968,866 discloses a catalyst comprising a chromium complex which contains a coordinating asymmetric tridentate phosphane, arsane, or stibane ligand (hydrocarbyl groups) and an alumoxane. Carter et al., Chem. Commun., 2002, pp. 858-859 disclosed an ethylene trimerization catalyst obtained by contacting a chromium source, ligands bearing ortho-methoxy-substituted aryl groups, and an alkyl alumoxane activator. Similarly, WO02/04119A1 discloses a catalyst comprising a source of chromium, molybdenum, or tungsten, and a ligand containing at least one phosphorus, arsenic, or antimony atom bound to at least one (hetero)hydrocarbyl group.

50 **[0012]** Other pertinent references include J. Am. Chem. Soc. 123, 7423-7424 (2001), WO01/68572A1, WO02/066404A1, WO04/056477, WO04/056478, WO04/056479, WO04/056480, EP1110930A1, U.S. Pat. Nos. 3,333,016, 5,439,862, 5,744,677, and 6,344,594 and U.S. Pat. App. Pub. No. 2002/0035029A1. Japanese patent application JP 2001187345A2 (Tosoh Corp., Japan) discloses ethylene trimerization catalysts comprising chromium complexes having ligands which are amines substituted with two (pyrazol-1-yl)methyl groups.

55 **[0013]** Although each of the above described catalysts is useful for the trimerization of ethylene, there remains a desire

to improve the performance of olefin oligomerization catalysts from the standpoint of productivity and selectivity for oligomers such as 1-hexene or 1-octene.

[0014] Several pyridyl amine catalyst complexes have been disclosed for the polymerization or copolymerization of ethylene, propylene, isobutylene, octene, and styrene by Symyx Technologies, Inc. in U.S. Pat. Nos. 6,713,577, 6,750,345, 6,706,829, 6,727,361, and 6,828,397. Pyridyl amines were also disclosed in U.S. Pat. Nos. 6,103,657 and 6,320,005, assigned to Union Carbide Chemical and Plastics Technology Corporation, in which zirconium was used as the metal center, and the catalyst complex was used to polymerize alphaolefins, and in U.S. Pat. No. 5,637,660, assigned to Lyondell Petrochemical Company, which also describes Group 4 complexes of pyridyl amine ligands. Robertson et al., Inorg. Chem. 42, pp 6875-6885 (2003), discloses chromium complexes of tris(2-pyridylmethyl)amine for ethylene polymerization.

[0015] US 6,437,161 discloses a chromium complex comprising a heterocyclic nitrogen containing five membered ring and an activating compound. Oligomerization is also disclosed.

[0016] WO 2004/083263 discloses a polymerization and oligomerization catalyst comprising a metal complex comprising five membered heterocyclic nitrogen containing compounds and an activator.

[0017] US 5,856,612 discloses a process for the preparation of alpha-olefin oligomers using a chromium based catalyst comprising a chromium compound, a nitrogen containing compound such as an amine, amide or imide and an alkyl aluminium compound. The reaction is carried out in a hydrocarbon solvent. The chromium compound may be complexes with heterocyclic amines such as pyridine or with five membered ring moieties such as cyclopentadiene.

[0018] US 6,844,290 discloses an oligomerization catalyst complex comprising a chromium containing triazacyclohexane complex and at least one activating additive. In one embodiment, the activating additive is a five membered aromatic nitrogen heterocycle and an alkyl aluminum compound.

[0019] JP 7 010 780 discloses a trimerization reaction of olefins using a catalyst complex comprising a chromium compound, an activating aluminum compound and a heterocyclic compound comprising nitrogen and a pyrrole or imidazole ring.

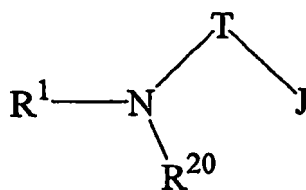
[0020] This invention also relates to US Patent Application Serial Nos. 60/611,943, 11/232,982 and 11/233,227.

[0021] What is needed is a catalyst system that can be readily prepared and that selectively oligomerizes ethylene or other olefins with both high activity and high selectivity.

SUMMARY OF THE INVENTION

[0022] The present invention provides methods and compositions to produce oligomers of olefins, comprising reacting olefins with a catalyst system. The oligomerization reaction has a selectivity of at least 70 mole percent for the desired oligomer. Typically the catalyst system is formed from the combination of:

- 1) a ligand characterized by the following general formula:



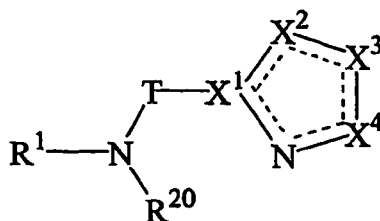
where R^1 and R^{20} can each be independently selected from the group consisting of hydrogen and optionally substituted hydrocarbyl, heteroatom containing hydrocarbyl and silyl, provided that R^1 or R^{20} do not equal T-J, where T-J can be as given by the general formula above and defined below; T can be a bridging group of the general formula $-(T'R^2R^3)-$, where T' is selected from the group consisting of carbon and silicon, R^2 and R^3 can each be independently selected from the group consisting of hydrogen, halogen, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, provided that two or more R^2 and/or R^3 groups may be joined together to form one or more optionally substituted ring systems having from 3-50 non-hydrogen atoms; J is an optionally substituted five-membered heterocycle, containing at least one nitrogen atom as part of the ring; with the further proviso that J contains at least two, but not more than four, heteroatoms;

2) a metal precursor compound characterized by the general formula $Cr(L)_n$ where each L can be independently selected from the group consisting of halide, alkyl, substituted alkyl, cycloalkyl, substituted cycloalkyl, heteroalkyl, substituted heteroalkyl heterocycloalkyl, substituted heterocycloalkyl, aryl, substituted aryl, heteroaryl, substituted

heteroaryl, alkoxy, aryloxy, hydroxy, boryl, silyl, amino, amine, hydrido, allyl, diene, seleno, phosphino, phosphine, ether, thioether, carboxylates, thio, 1,3-dionates, oxalates, carbonates, nitrates, sulfates, ethers, thioethers and combinations thereof, wherein two or more L groups may be combined in a ring structure having from 3 to 50 non-hydrogen atoms; n is 1, 2, 3, 4, 5, or 6; and

3) optionally, one or more activators.

[0023] In one embodiment, the ligand can be characterized by the following general formula:



where R^1 , R^{20} , and T are described above; and X^1 can be nitrogen or $-C(R^8)_{n'}$, X^2 , X^3 , and X^4 can be selected from the group consisting of oxygen, sulfur, $-C(R^8)_{n'}$, $-N(R^8)_{n'}$, and provided that at least one of X^1 , X^2 , X^3 , or X^4 is carbon or $-C(R^8)_{n'}$; each n' can be 1 or 2 and each n'' can be 0 or 1; and, each R^8 can be independently selected from the group consisting of hydrogen, halogen, nitro, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, and optionally two or more R^1 , R^{20} , R^2 , R^3 , and R^8 groups may be joined to form one or more optionally substituted ring systems.

[0024] In one embodiment, R^1 and R^{20} can each be independently selected from hydrogen and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, silyl and combinations thereof.

[0025] In another embodiment, R^1 is a hydrogen and R^{20} is an optionally substituted alkyl.

[0026] In another embodiment, R^1 is not hydrogen when R^{20} is a cyclic group.

[0027] In still another embodiment, R^{20} is not a hydrogen when R^1 is a cyclic group.

[0028] In another embodiment, R^1 and R^{20} can each be independently a ring having from 4-8 atoms in the ring generally selected from the group consisting of substituted cycloalkyl, heterocycloalkyl, aryl, and heteroaryl.

[0029] The ligand used in varying embodiments of the present invention can be thiazole-amine ligand B1 as shown in Fig. 1.

[0030] The ligand used in varying embodiments of the present invention can be selected from the thiazole-amine ligands C1 - C5 as shown in Fig. 2, especially ligands C1 and C5.

[0031] The ligand used in other embodiments of the present invention can be selected from the group consisting of the imidazole-amine ligands D1 - D3 seen in Fig. 3, especially ligand D1.

[0032] A ligand used in another embodiment of the present invention can be oxadiazole ligand E1 as seen in Fig. 4.

[0033] The activator used in the method of the present invention can be selected from the group consisting of modified methylalumoxane (MMAO), methylalumoxane (MAO), trimethylaluminum (TMA), triisobutyl aluminum (TIBA), polymethylalumoxane-IP (PMAO), N,N-di(n-decyl)-4-n-butyl-anilinium tetrakis(perfluorophenyl)borate, and mixtures thereof.

[0034] The metal precursor used in the method of the present invention can be selected from the group consisting of $(THF)_3CrMeCl_2$, $(THF)_3CrCl_3$, $(Mes)_3Cr(THF)$, $[(TFA)_2Cr(OEt_2)]_2$, $(THF)_3CrPh_3$, and mixtures thereof.

[0035] The method of the present invention can oligomerize, e.g. trimerize or tetramerize, C_2 to C_{12} olefins. In one embodiment of the present invention, the olefin can be ethylene. The oligomerization of ethylene can produce 1-hexene, 1-octene, or mixtures thereof. The reaction in the method of the present invention can occur in a hydrocarbon solvent.

[0036] Further aspects of this invention will be evident to those of skill in the art upon review of this specification.

BRIEF DESCRIPTION OF THE DRAWINGS

[0037]

Fig. 1 illustrates heteroaryl-amine (thiazole-amine) ligand B1 according to an embodiment of the invention.

Fig. 2 illustrates heteroaryl-amine (thiazole-amine) ligands C1 - C5 according to embodiments of the invention.

Fig. 3 illustrates heteroaryl-amine (imidazole-amine) ligands D1 - D3 according to embodiments of the invention.

Fig. 4 illustrates heteroaryl-amine (oxadiazole-amine) ligand E1 according to an embodiment of the invention.

DETAILED DESCRIPTION

[0038] The inventions disclosed herein include chromium metal complexes and compositions, which are useful as catalysts for the selective oligomerization of olefins, specifically C2 to C12 olefins and especially C2 to C8 olefins, including the trimerization and/or tetramerization of ethylene.

[0039] For the purposes of this invention and the claims thereto when an oligomeric material (such as a dimer, trimer, or tetramer) is referred to as comprising an olefin, the olefin present in the material is the reacted form of the olefin. Likewise, the active species in a catalytic cycle may comprise the neutral or ionic forms of the catalyst. In addition, a reactor is any container(s) in which a chemical reaction occurs.

[0040] As used herein, the new numbering scheme for the Periodic Table Groups is used as set out in Chemical and Engineering News, 63(5), 27 (1985).

[0041] As used herein, the phrase "characterized by the formula" is not intended to be limiting and is used in the same way that "comprising" is commonly used. The term "independently selected" is used herein to indicate that the groups in question - *e.g.*, R¹, R² and R³ - can be identical or different (*e.g.*, R¹, R² and R³ may all be substituted alkyls, or R¹ and R² may be a substituted alkyl and R³ may be an aryl,. Use of the singular includes use of the plural and vice versa (*e.g.*, a hexane solvent, includes hexanes). A named R group will generally have the structure that is recognized in the art as corresponding to R groups having that name. The terms "compound" and "complex" are generally used interchangeably in this specification, but those of skill in the art may recognize certain compounds as complexes and vice versa. In addition, the term "catalyst" will be understood by those of skill in the art to include either activated or unactivated forms of the molecules the comprise the catalyst, for example, a procatalyst and including complexes and activators or compositions of ligands, metal precursors and activators and optionally including scavengers. For purposes of this invention, a catalyst system is defined to be the combination of an activator and a metal ligand complex or the combination of an activator, a ligand and a metal precursor. A metal ligand complex is defined to be the product of the combination of a metal precursor and a ligand. For the purposes of illustration, representative certain groups are defined herein.

These definitions are intended to supplement and illustrate, not preclude, the definitions known to those of skill in the art.

[0042] "Optional" or "optionally" means that the subsequently described event or circumstance may or may not occur, and that the description includes instances where the event or circumstance occurs and instances where it does not. For example, the phrase "optionally substituted hydrocarbyl" means that a hydrocarbyl moiety may or may not be substituted and that the description includes both unsubstituted hydrocarbyl and hydrocarbyl where there is substitution.

[0043] The term "substituted" as in "substituted hydrocarbyl," "substituted aryl," "substituted alkyl," means that in the group in question (*i.e.*, the hydrocarbyl, alkyl, aryl or other moiety that follows the term), at least one hydrogen atom bound to a carbon atom is replaced with one or more substituent groups such as hydroxy, alkoxy, alkylthio, phosphino, amino, halo, silyl, like. When the term "substituted" introduces a list of possible substituted groups, it is intended that the term apply to every member of that group. That is, the phrase "substituted alkyl, alkenyl and alkynyl" is to be interpreted as "substituted alkyl, substituted alkenyl and substituted alkynyl." Similarly, "optionally substituted alkyl, alkenyl and alkynyl" is to be interpreted as "optionally substituted alkyl, optionally substituted alkenyl and optionally substituted alkynyl."

[0044] The term "saturated" refers to the lack of double and triple bonds between atoms of a radical group such as ethyl, cyclohexyl, pyrrolidinyl. The term "unsaturated" refers to the presence of one or more double and triple bonds between atoms of a radical group such as vinyl, allyl, acetylide, oxazoliny, cyclohexenyl, acetyl and specifically includes alkenyl and alkynyl groups, as well as groups in which double bonds are delocalized, as in aryl and heteroaryl groups as defined below.

[0045] The terms "cyclo" and "cyclic" are used herein to refer to saturated or unsaturated radicals containing a single ring or multiple condensed rings. Suitable cyclic moieties include, for example, cyclopentyl, cyclohexyl, cyclooctenyl, bicyclooctyl, phenyl, naphthyl, pyrrolyl, furyl, thiophenyl, imidazolyl. In particular embodiments, cyclic moieties include between 3 and 200 atoms other than hydrogen, between 3 and 50 atoms other than hydrogen or between 3 and 20 atoms other than hydrogen.

[0046] The term "hydrocarbyl" as used herein refers to hydrocarbyl radicals containing 1 to about 50 carbon atoms, specifically 1 to about 24 carbon atoms, most specifically 1 to about 16 carbon atoms, including branched or unbranched, cyclic or acyclic, saturated or unsaturated species, such as alkyl groups, alkenyl groups, aryl groups.

[0047] The term "alkyl" as used herein refers to a branched or unbranched saturated hydrocarbon group typically although not necessarily containing 1 to about 50 carbon atoms, such as methyl, ethyl, *n*-propyl, isopropyl, *n*-butyl, isobutyl, *sec*-butyl, *t*-butyl, octyl, decyl, as well as cycloalkyl groups such as cyclopentyl, cyclohexyl. Generally, although again not necessarily, alkyl groups herein may contain 1 to about 20 carbon atoms.

[0048] The term "alkenyl" as used herein refers to a branched or unbranched, cyclic or acyclic hydrocarbon group typically, although not necessarily, containing 2 to about 50 carbon atoms and at least one double bond, such as ethenyl, *n*-propenyl, isopropenyl, *n*-butenyl, isobutenyl, octenyl, decenyl. Generally, although again not necessarily, alkenyl groups herein contain 2 to about 20 carbon atoms.

[0049] The term "alkynyl" as used herein refers to a branched or unbranched, cyclic or acyclic hydrocarbon group typically although not necessarily containing 2 to about 50 carbon atoms and at least one triple bond, such as ethynyl, *n*-propynyl, isopropynyl, *n*-butynyl, isobutynyl, octynyl, decynyl, and the like. Generally, although again not necessarily, alkynyl groups herein may have 2 to about 20 carbon atoms.

[0050] The term "aromatic" is used in its usual sense, including unsaturation that is delocalized across several bonds around a ring. The term "aryl" as used herein refers to a group containing an aromatic ring. Aryl groups herein include groups containing a single aromatic ring or multiple aromatic rings that are fused together, linked covalently, or linked to a common group such as a methylene or ethylene moiety. More specific aryl groups contain one aromatic ring or two or three fused or linked aromatic rings, e.g., phenyl, naphthyl, biphenyl, anthracenyl, or phenanthrenyl. In particular embodiments, aryl substituents include 1 to about 200 atoms other than hydrogen, typically 1 to about 50 atoms other than hydrogen, and specifically 1 to about 20 atoms other than hydrogen. In some embodiments herein, multi-ring moieties are substituents and in such embodiments the multi-ring moiety can be attached at an appropriate atom. For example, "naphthyl" can be 1-naphthyl or 2-naphthyl; "anthracenyl" can be 1-anthracenyl, 2-anthracenyl or 9-anthracenyl; and "phenanthrenyl" can be 1-phenanthrenyl, 2-phenanthrenyl, 3-phenanthrenyl, 4-phenanthrenyl, or 9-phenanthrenyl.

[0051] The term "alkoxy" as used herein intends an alkyl group bound through a single, terminal ether linkage; that is, an "alkoxy" group may be represented as -O-alkyl where alkyl is as defined above. The term "aryloxy" is used in a similar fashion, and may be represented as -O-aryl, with aryl as defined below. The term "hydroxy" refers to -OH.

[0052] Similarly, the term "alkylthio" as used herein intends an alkyl group bound through a single, terminal thioether linkage; that is, an "alkylthio" group may be represented as -S-alkyl where alkyl is as defined above. The term "arylthio" is used similarly, and may be represented as -S-aryl, with aryl as defined below. The term "mercapto" refers to -SH.

[0053] The terms "halo" and "halogen" are used in the conventional sense to refer to a chloro, bromo, fluoro or iodo radical.

[0054] The terms "heterocycle" and "heterocyclic" refer to a cyclic radical, including ring-fused systems, including heteroaryl groups as defined below, in which one or more carbon atoms in a ring is replaced with a heteroatom - that is, an atom other than carbon, such as nitrogen, oxygen, sulfur, phosphorus, boron or silicon. Heterocycles and heterocyclic groups include saturated and unsaturated moieties, including heteroaryl groups as defined below. Specific examples of heterocycles include pyridine, pyrrolidine, pyrroline, furan, tetrahydrofuran, thiophene, imidazole, oxazole, thiazole, indole, including any isomers of these. Additional heterocycles are described, for example, in Alan R. Katritzky, Handbook of Heterocyclic Chemistry, Pergamon Press, 1985, and in Comprehensive Heterocyclic Chemistry, A.R. Katritzky et al., eds., Elsevier, 2d. ed., 1996. The term "metallocycle" refers to a heterocycle in which one or more of the heteroatoms in the ring or rings is a metal.

[0055] The term "heteroaryl" refers to an aryl radical that includes one or more heteroatoms in the aromatic ring. Specific heteroaryl groups include groups containing heteroaromatic rings such as thiophene, pyridine, pyrazine, isoxazole, pyrazole, pyrrole, furan, thiazole, oxazole, imidazole, isothiazole, oxadiazole, triazole, and benzo-fused analogues of these rings, such as indole, carbazole, benzofuran, benzothiophene.

[0056] More generally, the modifiers "hetero" and "heteroatom-containing", as in "heteroalkyl" or "heteroatom-containing hydrocarbyl group" refer to a molecule or molecular fragment in which one or more carbon atoms is replaced with a heteroatom. Thus, for example, the term "heteroalkyl" refers to an alkyl substituent that is heteroatom-containing. When the term "heteroatom-containing" introduces a list of possible heteroatom-containing groups, it is intended that the term apply to every member of that group. That is, the phrase "heteroatom-containing alkyl, alkenyl and alkynyl" is to be interpreted as "heteroatom-containing alkyl, heteroatom-containing alkenyl and heteroatom-containing alkynyl."

[0057] By "divalent" as in "divalent hydrocarbyl", "divalent alkyl", "divalent aryl", is meant that the hydrocarbyl, alkyl, aryl or other moiety is bonded at two points to atoms, molecules or moieties with the two bonding points being covalent bonds.

[0058] As used herein the term "silyl" refers to the $-SiZ^1Z^2Z^3$ radical, where each of Z^1 , Z^2 , and Z^3 is independently selected from the group consisting of hydrogen and optionally substituted alkyl, alkenyl, alkynyl, heteroatom-containing alkyl, heteroatom-containing alkenyl, heteroatom-containing alkynyl, aryl, heteroaryl, alkoxy, aryloxy, amino, silyl and combinations thereof.

[0059] As used herein the term "boryl" refers to the $-BZ^1Z^2$ group, where each of Z^1 and Z^2 is as defined above. As used herein, the term "phosphino" refers to the group $-PZ^1Z^2$, where each of Z^1 and Z^2 is as defined above. As used herein, the term "phosphine" refers to the group $:PZ^1Z^2Z^3$, where each of Z^1 , Z^3 and Z^2 is as defined above. The term "amino" is used herein to refer to the group $-NZ^1Z^2$, where each of Z^1 and Z^2 is as defined above. The term "amine" is used herein to refer to the group $:NZ^1Z^2Z^3$, where each of Z^1 , Z^2 and Z^3 is as defined above.

[0060] In this specification, the metal-ligand complexes are sometimes referred to as, for example, (2,1) complexes or (3,1) complexes, with the first number representing the number of coordinating atoms and second number representing the number of anionic sites on the heterocycle-amine ligand, when the metal-ligand bonding is considered from an ionic bonding model perspective, with the metal considered to be cationic and the ligand considered to be anionic. From a covalent bonding model perspective, a (2,1) complex may be considered to be a complex in which the heterocycle-

amine ligand is bound to the metal center via one covalent bond and one dative bond, while a (3,1) complex may be considered to be a complex in which the heterocycle-amine ligand is bound to the metal center via one covalent bond and two dative bonds.

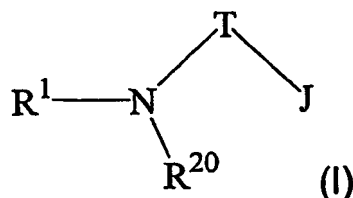
[0061] Throughout the Figures and the following text, several abbreviations may be used to refer to specific compounds or elements. Abbreviations for atoms are as given in the periodic table (Li = lithium, for example). Other abbreviations that may be used are as follows: "*i*-Pr" to refer to isopropyl; "*t*-Bu" to refer to *tertiary*-butyl; "*i*-Bu" to refer to isobutyl; "Me" to refer to methyl; "Et" to refer to ethyl; "Ph" to refer to phenyl; "Mes" to refer to mesityl (2,4,6-trimethyl phenyl); "TFA" to refer to trifluoroacetate; "THF" to refer to tetrahydrofuran; "TsOH" to refer to *para*-toluenesulfonic acid; "cat." to refer to catalytic amount of; "LDA" to refer to lithium diisopropylamide; "DMF" to refer to dimethylformamide; "eq." to refer to molar equivalents; "TMA" to refer to AlMe₃; "TIBA" to refer to Al *i*-(Bu)₃. SJ₂BF₂₀ refers to [(n-C₁₀H₂₁)₂(4-n-C₄H₉-C₆H₄)NH][B(C₆F₅)₄].

[0062] This invention relates to methods for selectively oligomerizing (e.g., trimerizing and/or tetramerizing) C₂ to C₁₂ olefins, specifically ethylene, comprising reacting a catalytic composition or compound(s), optionally with one or more activators, with the olefin. As referred to herein, selective oligomerization refers to producing the desired oligomer with a selectivity of the reaction being at least 70%, more specifically at least 80% by mole of oligomer, with the possibility that an acceptable amount of polymer is present, but with the preference that no polymer is present in the product. In other embodiments, less than 20 weight % of polymer is present, specifically less than 5 weight %, more specifically less than 2 weight %, based upon the total weight of monomer converted to oligomers and polymers, where a polymer is defined to mean a molecule comprising more than 100 mers. In other embodiments, selective oligomerization refers to producing two desired oligomers, with the selectivity of the two desired oligomers summing to at least 80% by sum of mole of oligomers.

[0063] In another embodiment, this invention relates to a method to trimerize or tetramerize a C₂ to C₁₂ olefin wherein the method produces at least 70 % selectivity for the desired oligomer(s) (specifically at least 80%, specifically at least 85%, specifically at least 90 %, specifically at least 95 %, specifically at least 98%, specifically at least 99%, specifically 100%), calculated based upon the amount of the desired oligomer produced relative to the total yield; and at least 70% of the olefin monomer reacts to form product (specifically at least 80%, specifically at least 85%, specifically at least 90 %, specifically at least 95 %, specifically at least 98%, specifically at least 99%, specifically 100%).

[0064] This invention may also relate to novel metal ligand complexes and or novel combinations of specific ligands disclosed herein and metal precursors.

[0065] The methods of this invention specifically contact the desired monomers with a metal ligand complex or a combination of a ligand and a metal precursor (and optional activators) to form the desired oligomer. Preferred ligands useful in the present invention may be characterized by the general formula:



where R¹ and R²⁰ are each independently selected from the group consisting of hydrogen and optionally substituted hydrocarbyl, heteroatom containing hydrocarbyl and silyl. In some embodiments, R¹ and R²⁰ are each independently selected from hydrogen and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, silyl and combinations thereof. In certain embodiments, R¹ and R²⁰ are each independently a ring having from 4-8 atoms in the ring selected from the group consisting of substituted cycloalkyl, heterocycloalkyl, aryl and heteroaryl, provided that R¹ and R²⁰ do not equal T-J, where T-J is as shown in Formula (I) above and defined below.

[0066] T is a bridging group characterized by the general formula -(T'R²R³)-, where each T' is independently selected from the group consisting of carbon and silicon, R² and R³ are independently selected from the group consisting of hydrogen, halogen, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, provided that two or more R² and/or R³ groups may be joined together to form one or more optionally substituted ring systems, such as saturated, unsaturated or aromatic ring systems having from 3-50 non-hydrogen atoms (e.g., cyclopropyl, where T'=C, and R² and R³ together form -CH₂-CH₂-; or cyclohexyl, where T'=C and the two R² groups together form -CH₂-CH₂-CH₂-CH₂-).

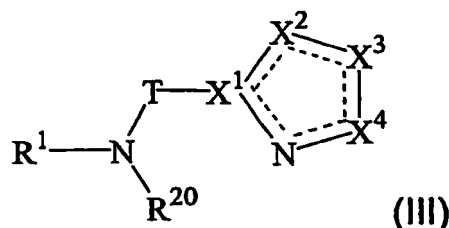
[0067] J is an optionally substituted five-membered heterocycle, containing at least one nitrogen atom as part of the ring. In some embodiments, J is specifically a five-membered heteroaryl containing at least one nitrogen atom as part of the ring. J is a five-membered heterocycle, the heterocycle contains at least two but no more than four heteroatoms.

In more particular embodiments, at least one of the heteroatoms is a nitrogen, oxygen, or sulfur in a ring position adjacent to the ring atom that is bonded to T.

[0068] In more specific embodiments, R^1 and R^{20} are each independently selected from the group consisting of hydrogen, alkyl, substituted alkyl, aryl, substituted aryl, heteroaryl, substituted heteroaryl and combinations thereof. Even more specifically, R^{20} is hydrogen and R^1 is selected from the group consisting of alkyl, substituted alkyl, aryl, and substituted aryl.

[0069] In some other embodiments, R^2 is hydrogen, and R^3 is selected from the group consisting of aryl, substituted aryl, heteroaryl, substituted heteroaryl, primary and secondary alkyl groups, and $-PY_2$ where Y is selected from the group consisting of aryl, substituted aryl, heteroaryl, and substituted heteroaryl.

[0070] In one embodiment, the heterocycle-amine ligands can be characterized as ligands where J is a five-membered heterocycle or substituted heterocycle group. These ligands may be characterized by the general formula:



where R^1 , R^{20} , and T are as described above.

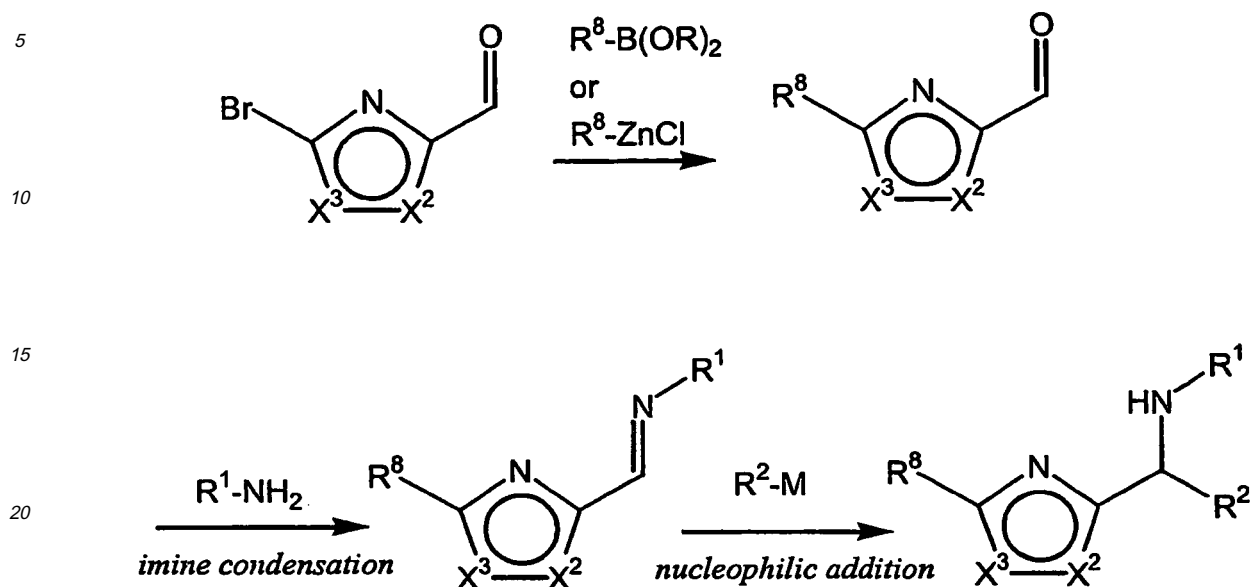
[0071] In Structure (III) (and throughout this specification), the presence of one solid line and one dashed line between any pair of atoms is intended to indicate that the bond in question may be a single bond or a double bond, or a bond with bond order intermediate between single and double, such as the delocalized bonding in an aromatic ring. In some embodiments of the structure of formula III, X^1 is nitrogen or $-C(R^8)_{n'}$, X^2 , X^3 , and X^4 are selected from the group consisting of oxygen, sulfur, $-C(R^8)_{n'}$, $-N(R^8)_{n''}$, and provided that X^1 is $-C(R^8)_{n'}$ or at least one of X^2 , X^3 , or X^4 is $-C(R^8)_{n'}$ (within the above definitions), each n' is 1 or 2 and each n'' is 0 or 1 (depending, e.g., on the degree of saturation of the ring). Each R^8 is independently selected from the group consisting of hydrogen, halogen, nitro, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, and optionally two or more R^1 , R^{20} , R^2 , R^3 , and R^8 groups may be joined to form one or more optionally substituted ring systems. In more specific embodiments, the heterocycle ring in formula III is an optionally substituted heteroaryl ring, where n' is 1 and n'' is 0 or 1, and provided that when X^1 is $-C(R^8)_{n'}$, n'' is 0.

[0072] In certain more specific embodiments, X^4 is selected from the group consisting of $-C(R^9)$ - wherein R^9 is specifically selected from the group consisting of optionally substituted aryl and heteroaryl.

[0073] The detailed synthesis of certain types of heterocycle-amine ligands are specifically discussed below, including thiazole-amine ligands, imidazole-amine ligands, and oxadiazole-amine ligands. Those of ordinary skill in the art will be able to synthesize other embodiments.

[0074] Thiazole-amine ligands can be prepared according to the general reaction scheme outlined in Scheme 2, in which a substituted thiazole-amine aldehyde is prepared from the corresponding bromo-aldehyde in a coupling reaction. The resultant substituted thiazole-amine aldehyde is then reacted with a primary amine to form the intermediate imine, which is then reacted with a nucleophile to provide the corresponding amine.

Scheme 2.



where R^8 , X^3 , X^2 , R^1 , R^2 and M are as defined above. R can be any suitable hydrocarbyl.

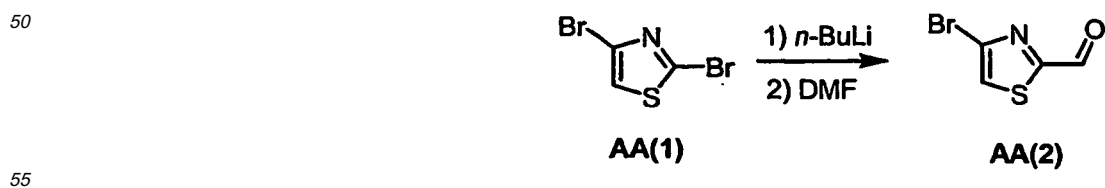
[0075] Generally, R^2M is a nucleophile such as an alkylating, arylating or hydrogenating reagent and M is a metal such as a main group metal, or a metalloid such as boron. The alkylating, arylating or hydrogenating reagent may be a Grignard, alkyl or aryl-lithium or borohydride reagent. In step 4, a complexing agent such as magnesium bromide can be used to direct the nucleophile selectively to the imine carbon, as described in U.S. Pat. Nos. 6,750,345 and 6,713,577. R^3 can be installed (into the bridging group T , and as defined above in relation to Formula (I) above) through nucleophilic addition to the appropriate ketimine, which can be obtained through a variety of known synthetic procedures.

[0076] In the reaction scheme shown in Scheme 2, from formula (III), X^1 is shown as carbon and X^4 is shown as CR^8 . R^3 can be installed (into the bridging group T , and as defined above in relation to Formula (I) above) through nucleophilic addition to the appropriate ketimine, which can be obtained through a variety of known synthetic procedures. Using this approach, it is possible in many embodiments to introduce a wide variety of diverse substituents in the ligands of the invention, which can be significant in the design of libraries or arrays for high throughput or combinatorial methods.

[0077] For ligands where the appropriate bromo-thiazole aldehyde is not commercially available, a variety of alternative synthetic techniques can be used. In some such embodiments, the aldehyde can be prepared from commercially available precursors, with the group in the R^8 position being installed either before or after the introduction of the aldehyde substituent, depending on the particular chemistry.

[0078] Thus, for example, commercially available di-bromo thiazole AA(1) can be used as the starting point in the preparation of a variety of thiazole-amine (i.e., (thiazol-2-yl)-alkyl amine) ligands, such as ligand B1, as illustrated in Fig. 1, yielding bromo-aldehyde AA(2) upon regioselective lithium-halide exchange, followed by DMF addition as shown in Scheme 3. AA(2) can then be further functionalized according to the reaction scheme illustrated in Scheme 2, as discussed above.

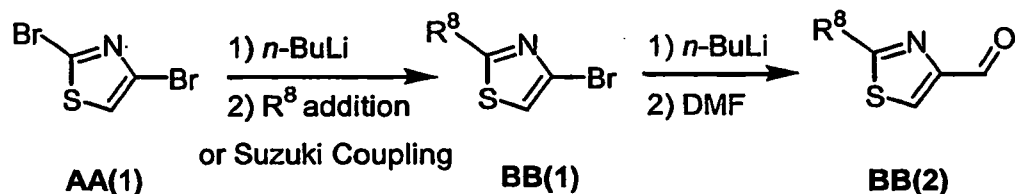
Scheme 3.



[0079] Similarly, AA(1) can also be used to prepare (thiazol-4-yl)-alkyl amine ligands (e.g., ligands selected from C1-C5, as illustrated in Fig. 2) as shown by the reaction scheme illustrated in Scheme 4. The bromo group first replaced in

Scheme 4 is believed to be more reactive and undergoes lithium-halide exchange first. Subsequent R⁸ addition (e.g. through Suzuki coupling) gives BB(1). Aldehyde BB(2) can then be generated by a second lithium-halide exchange followed by addition of DMF.

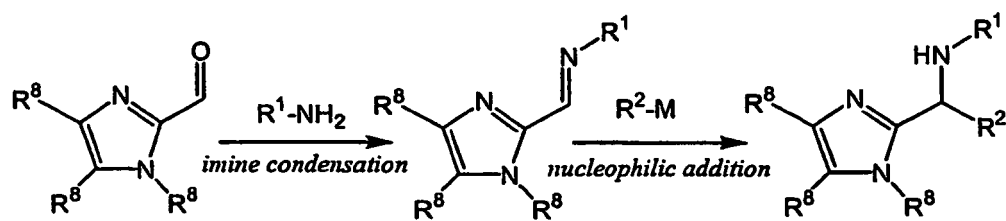
Scheme 4.



where R⁸ is as defined above.

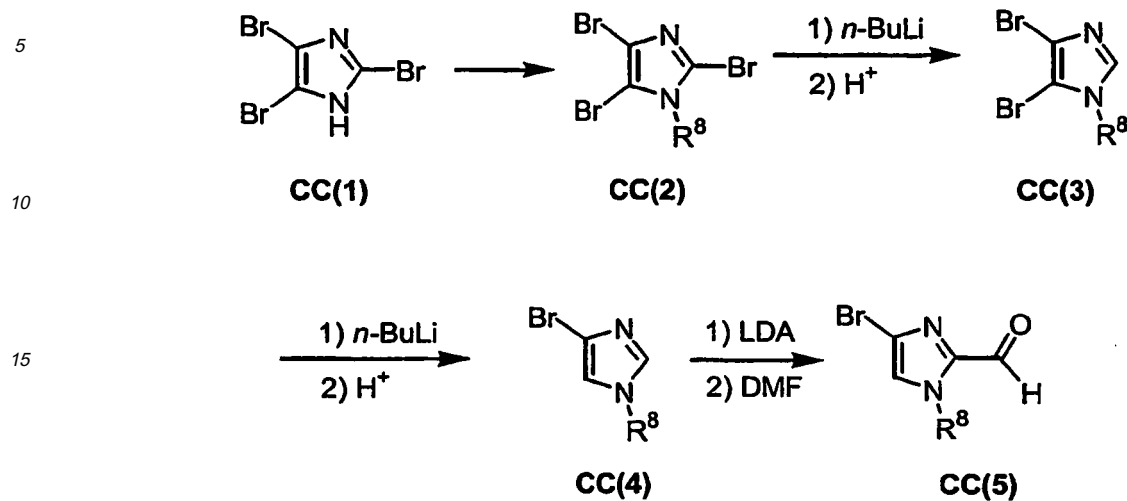
[0080] In the case of imidazole-containing ligands (e.g., imidazole-amines refer to ((imidazol-2-yl)-alkyl amines) and ((imidazol-4-yl)-alkyl amines)), the imidazole ring can be prepared using known techniques, as described, for example, in Heterocycles 39, pp 139-153 (1994) and illustrated in Scheme 5.

Scheme 5.



where R¹, R² and R⁸ are as defined above, and R³ can be installed (into the bridging group T, and as defined above in relation to Formula (I) above) through nucleophilic addition to the appropriate ketimine, which can be obtained through a variety of known synthetic procedures. A number of approaches can be used for installation of the various possible R⁸ substituents, as illustrated by the Schemes 6 - 9 below. One approach begins with commercially available tribromoimidazole CC(2) or CC(1), as shown in Scheme 6. Two of the three bromine substituents in CC(2) can be removed in a regioselective manner because of the difference in reactivities, and the resulting bromo-imidazole CC(4) can then be further functionalized by treatment with LDA, followed by DMF addition to give desired aldehyde CC(5). Where the appropriate tribromoimidazole CC(2) is not commercially available, it can be obtained through R⁸ substitution of tribromoimidazole CC(1). In many cases, bromo-imidazole CC(4) can also be accessed directly through substitution of 4-bromo-imidazole, which is commercially-available.

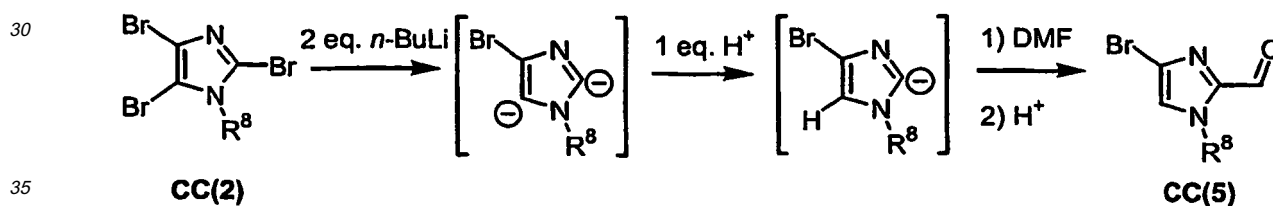
Scheme 6.



where R⁸ is as defined above.

[0081] Aldehyde CC(5) can also be generated in a one-pot reaction from the tribromo-imidazole CC(2), as shown in Scheme 7, where the tribromo-imidazole is first treated with 2 equivalents of *n*-BuLi, followed by addition of 1 equivalent of acid and subsequent treatment with DMF.

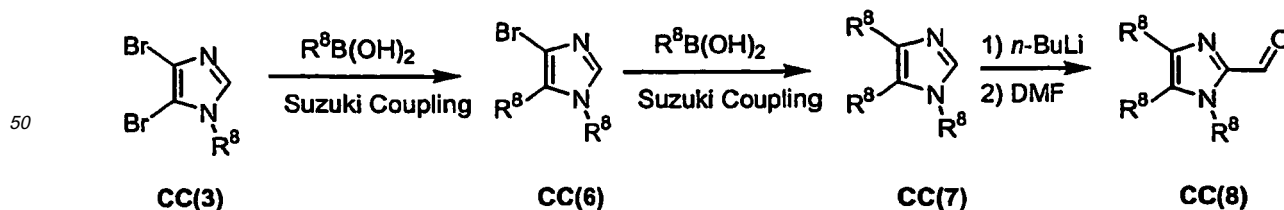
Scheme 7.



where R⁸ is as defined above.

[0082] Dibromoimidazole CC(3) can be used as an access point for functionalization at the R⁸ position shown specifically in Scheme 8. The difference in reactivity of the two bromo substituents makes it possible to install different R groups at the various R⁸ positions regioselectively, via sequential Suzuki coupling reactions using different boronic acids to give the aldehyde CC(8), as shown in Scheme 8.

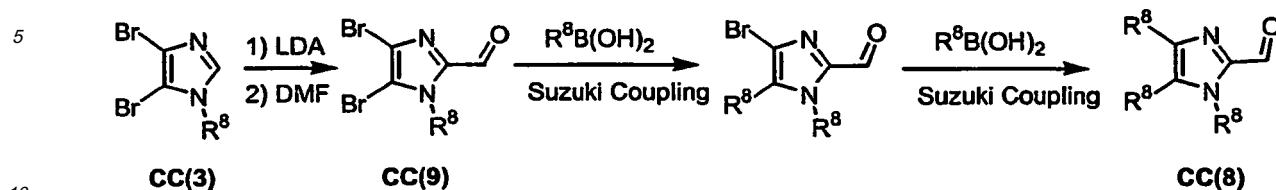
Scheme 8.



where each R⁸ is, independently, as defined above.

[0083] Aldehyde CC(8) may also be prepared by first installing the aldehyde (to give CC(9)), followed by sequential Suzuki coupling reactions, as shown in Scheme 9.

Scheme 9.

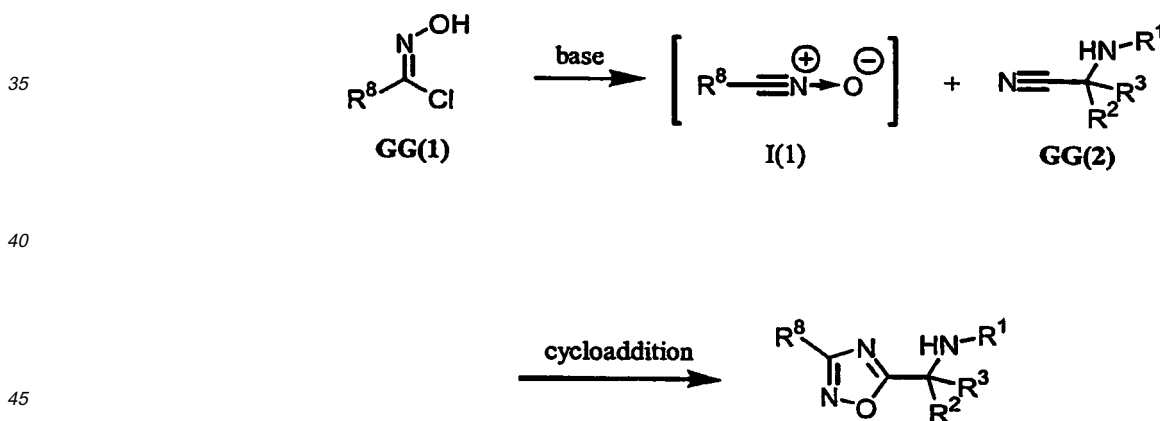


where each R^8 is, independently, as defined above.

[0084] Additionally, for thiazole-amine and imidazole-amine ligands, when R^{20} is not hydrogen, the R^{20} group may be installed through condensation of the aldehyde with a secondary amine, through nucleophilic addition of $R^{20}M$ to the imine nitrogen, or through a variety of other known synthetic procedures.

[0085] Oxadiazole amine ligands can be synthesized by the cycloaddition of hydroximinoyl chlorides with nitriles as depicted in Scheme 10, below. GG(1) is converted, in situ, to the nitrile oxide dipole I(1) in the presence of base (Liu, et al., J. Org. Chem. 45, pp 3916-3918 (1980), which then undergoes a 3+2 cycloaddition with GG(2) (see Torsell, Nitrile Oxides, Nitrones, and Nitronates in Organic Synthesis; VCH: New York, 1988, pp. 55-74 and Jager, et al., "Nitrile Oxides," in Synthetic Applications of 1,3-Dipolar Cycloaddition Chemistry Toward Heterocycles and Natural Products; Padwa, et al., Eds.; Wiley: Chichester, 2002). I(1) can also be formed by other methods; see Carriera, et al., Org. Lett. 2, pp 539-541 (2000), and Sibi, et al., J. Am. Chem. Soc. 126, pp 5366-5367 (2004). Some examples of hydroximinoyl chlorides GG(1) are commercially available or can be prepared using known procedures (see, for example, the references cited above). Examples of GG(2), when R^2 and $R^3 = H$, or when $R^2 = \text{aryl}$ and $R^3 = H$, can be prepared according to known procedures (Jones, et al., J. Med. Chem. 28, pp 1468-1476 (1985); McEwen, et al., J. Org. Chem. 45, pp 1301-1308 (1980)). Alternatively GG(2) might be synthesized by cyanation of imines (see Naim, et al., Indian J. Chem. 19B, pp 622-624 (1980); Kobayashi, et al., J. Am. Chem. Soc. 119, pp 10049-10053 (1997)).

Scheme 10.



where R^1 , R^2 , R^3 , and R^8 are as defined above.

[0086] Alternative strategies to the reaction schemes illustrated in Schemes 2 - 10 can also be employed.

[0087] Once the desired ligand is formed, it can be combined with a Cr atom, ion, compound or other Cr precursor compound, and in some embodiments the present invention encompasses compositions that include any of the above-mentioned ligands in combination with an appropriate Cr precursor and an optional activator. For example, in some embodiments, the Cr precursor can be an activated Cr precursor, which refers to a Cr precursor (described below) that has been combined or reacted with an activator (described below) prior to combination or reaction with the ancillary ligand. As noted above, in one aspect the invention provides compositions that include such combinations of ligand and Cr atom, ion, compound or precursor. In some applications, the ligands are combined with a Cr compound or precursor and the product of such combination is not determined, if a product forms. For example, the ligand may be added to a reaction vessel at the same time as the Cr precursor compound along with the reactants, activators, scavengers,.

Additionally, the ligand can be modified prior to addition to or after the addition of the Cr precursor, e.g., through a deprotonation reaction or some other modification.

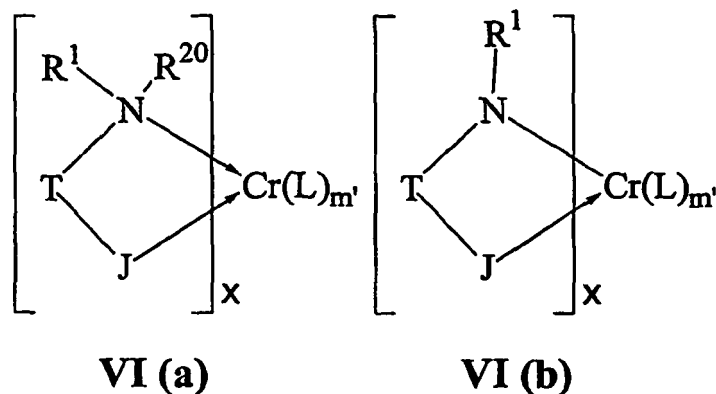
[0088] The Cr metal precursor compounds may be characterized by the general formula $\text{Cr}(\text{L})_n$ where L is an organic group, an inorganic group, or an anionic atom; and n is an integer of 1 to 6, and when n is not less than 2, L may be the same or different from each other. Each L is a ligand independently selected from the group consisting of hydrogen, halogen, optionally substituted alkyl, heteroalkyl, allyl, diene, alkenyl, heteroalkenyl, alkynyl, heteroalkynyl, aryl, heteroaryl, alkoxy, aryloxy, boryl, silyl, amino, phosphino, ether, thioether, phosphine, amine, carboxylate, alkylthio, arylthio, 1,3-donate, oxalate, carbonate, nitrate, sulfate, and combinations thereof. Optionally, two or more L groups are joined into a ring structure. One or more of the ligands L may be ionically bonded to Cr and, for example, L may be a non-coordinated or loosely coordinated or weakly coordinated anion (e.g., L may be selected from the group consisting of those anions described below in the conjunction with the activators). See Marks et al., Chem. Rev. 100, pp 1391-1434 (2000) for a detailed discussion of these weak interactions. The chromium precursors may be monomeric, dimeric or higher orders thereof.

[0089] Specific examples of suitable chromium precursors include, but are not limited to $(\text{THF})_3\text{CrMeCl}_2$, $(\text{Mes})_3\text{Cr}(\text{THF})$, $[\{\text{TFA}\}_2\text{Cr}(\text{OEt}_2)]_2$, $(\text{THF})_3\text{CrPh}_3$, $\text{CrCl}_3(\text{THF})_3$, $\text{CrCl}_4(\text{NH}_3)_2$, $\text{Cr}(\text{NMe}_3)_2\text{Cl}_3$, CrCl_3 , $\text{Cr}(\text{acac})_3$ (acac = acetylacetonate), $\text{Cr}(\text{2-ethylhexanoate})_3$, $\text{Cr}(\text{neopentyl})_4$, $\text{Cr}(\text{CH}_2\text{-C}_6\text{H}_4\text{-o-NMe}_2)_3$, $\text{Cr}(\text{TFA})_3$, $\text{Cr}(\text{CH}(\text{SiMe}_3)_2)_3$, $\text{Cr}(\text{Mes})_2(\text{THF})_3$, $\text{Cr}(\text{Mes})_2(\text{THF})$, $\text{Cr}(\text{Mes})\text{Cl}(\text{THF})_2$, $\text{Cr}(\text{Mes})\text{Cl}(\text{THF})_{0.5}$, $\text{Cr}(\text{p-tolyl})\text{Cl}_2(\text{THF})_3$, $\text{Cr}(\text{diisopropylamide})_3$, $\text{Cr}(\text{picolinate})_3$, $[\text{Cr}_2\text{Me}_8][\text{Li}(\text{THF})]_4$, $\text{CrCl}_2(\text{THF})$, $\text{Cr}(\text{NO}_3)_3$, $[\text{CrMe}_6][\text{Li}(\text{Et}_2\text{O})]_3$, $[\text{CrPh}_6][\text{Li}(\text{THF})]_3$, $[\text{CrPh}_6][\text{Li}(\text{n-Bu}_2\text{O})]_3$, $[\text{Cr}(\text{C}_4\text{H}_8)_3][\text{Li}(\text{THF})]_3$, and other well known chromium compounds commonly used as precursors in the formation of Cr complexes and catalysts.

[0090] The ligand may be mixed with a suitable metal precursor compound prior to or simultaneously with allowing the mixture to be contacted with the reactants (e.g., monomers). In this context, the ligand to metal precursor compound ratio can be in the range of 0.01:1 to 100:1, more specifically in the range of 0.1:1 to 10:1.

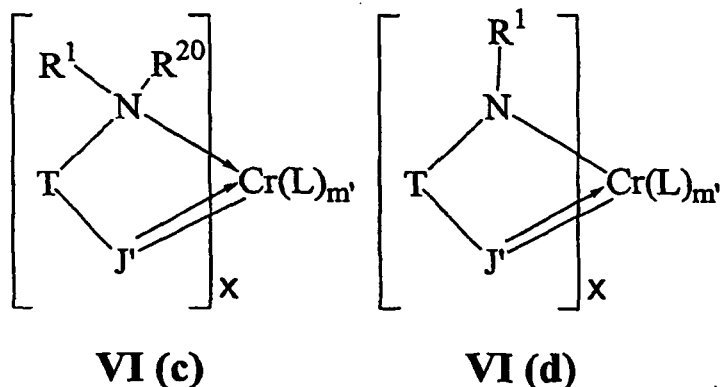
[0091] Generally, the ligand (or optionally a modified ligand as discussed above) is mixed with a suitable Cr precursor (and optionally other components, such as an activator, or a reagent to exchange L groups on the chromium after contact between the chromium precursor and the ligand; e.g., $\text{Li}(\text{acac})$) prior to or simultaneously with allowing the mixture to be contacted with the reactants (e.g., monomers). When the ligand is mixed with the Cr precursor compound, a Cr-ligand complex may be formed, which may itself be an active catalyst or may be transformed into a catalyst upon activation. In some embodiments the Cr precursor is contacted with other ligands, then activators, then monomers.

[0092] Cr-ligand complexes can take a number of different coordination modes. General examples of possible coordination modes include those characterized by the following general formulas:



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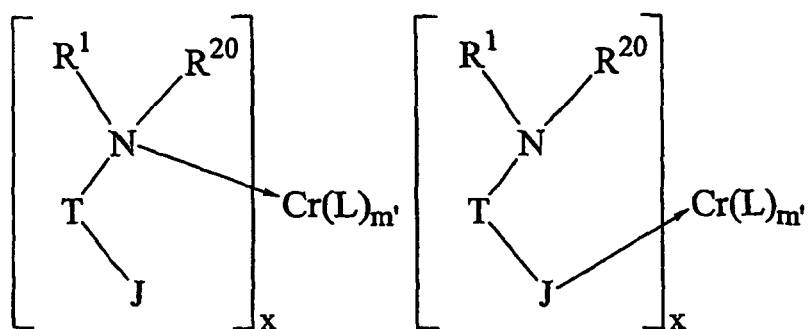
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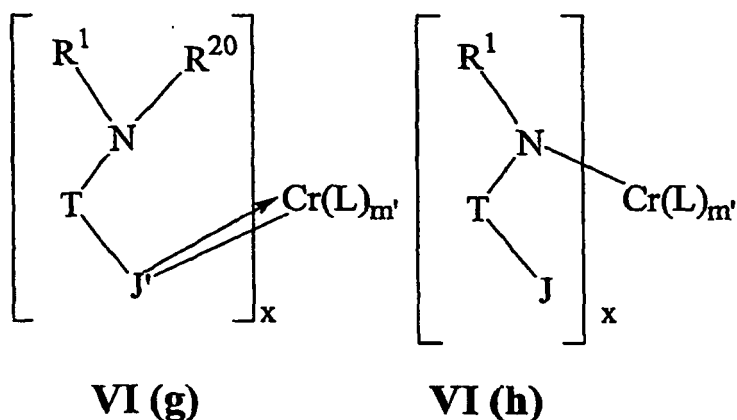
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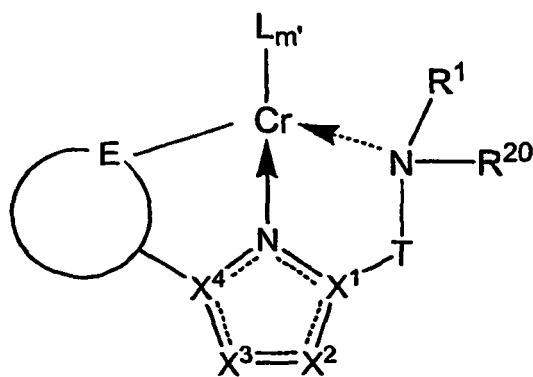
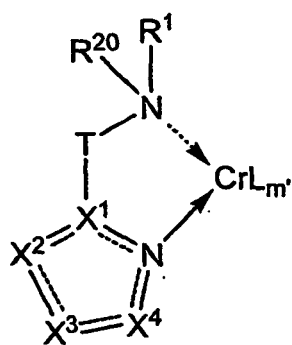
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wherein R^1 , R^{20} , L, J and T are described above; x is 1 or 2; and m' is 1, 2, 3, 4, or 5. J' is defined the same as J is defined above, provided that J' includes 2 atoms bonded to the Cr, one of the which is in the ring position adjacent to the atom bonded to T, which is bonded to Cr through a dative bond, and the other of which is bonded to the Cr through a covalent bond. The more specific embodiments of the ligands (e.g., formulas I and III) may replace the coordinated ligands drawn in formulae VI. Numerous other coordination modes are possible, for example the ligands may bind to two chromium metal centers in a bridging fashion (see for example Cotton and Walton, Multiple Bonds Between Metal Atoms 1993, Oxford University Press). Some studies (for example, Rensburg et al., Organometallics 23, pp1207-1222 (2004)) suggest that the ligand environment around Cr may be different at different points in the catalytic cycle. Hemilabile ligands, which can change their binding mode to the metal, may be useful in this regard.

[0093] In some embodiments, the ligand will be mixed with a suitable metal precursor prior to or simultaneous with

allowing the mixture to be contacted to the reactants. When the ligand is mixed with the metal precursor, a metal-ligand complex may be formed. In connection with the metal-ligand complex and depending on the ligand or ligands chosen, the metal-ligand complex may take the form of dimers, trimers or higher orders thereof or there may be two or more metal atoms that are bridged by one or more ligands. Furthermore, two or more ligands may coordinate with a single metal atom. The exact nature of the metal-ligand complex(es) formed depends on the chemistry of the ligand and the method of combining the metal precursor and ligand, such that a distribution of metal-ligand complexes may form with the number of ligands bound to the metal being greater than, equal to or less than the number of equivalents of ligands added relative to an equivalent of metal precursor.

[0094] Listed below are some examples of Cr-Ligand complex embodiments

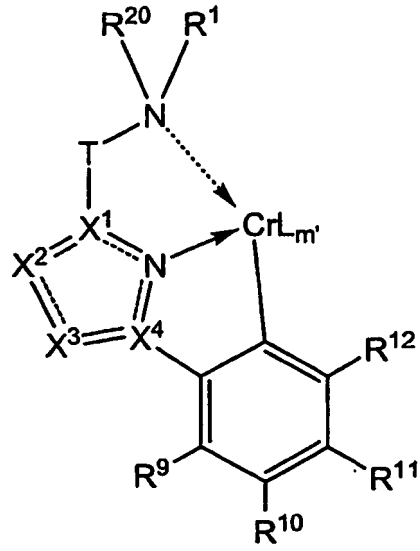


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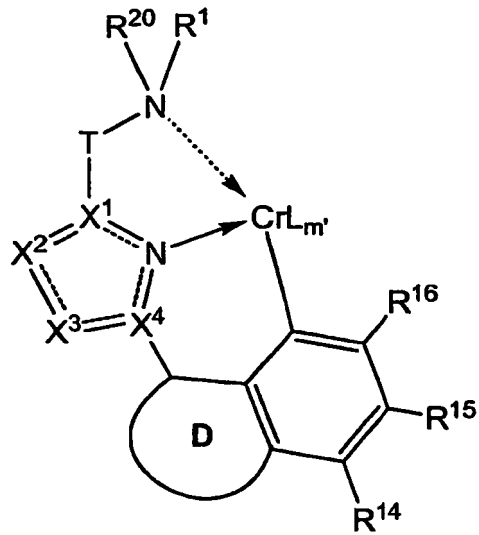


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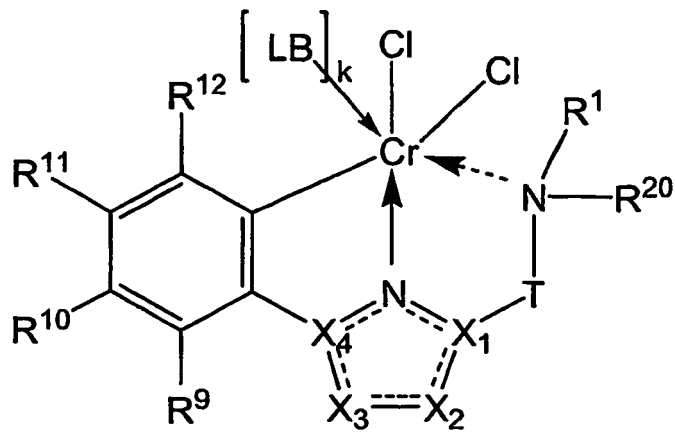
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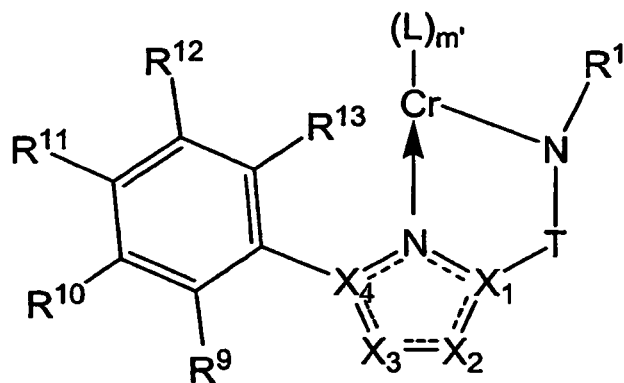
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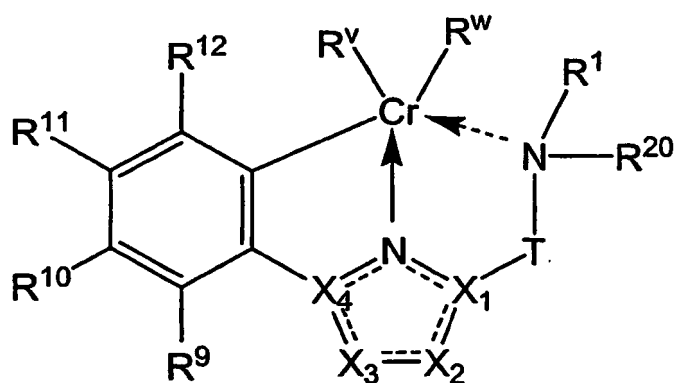
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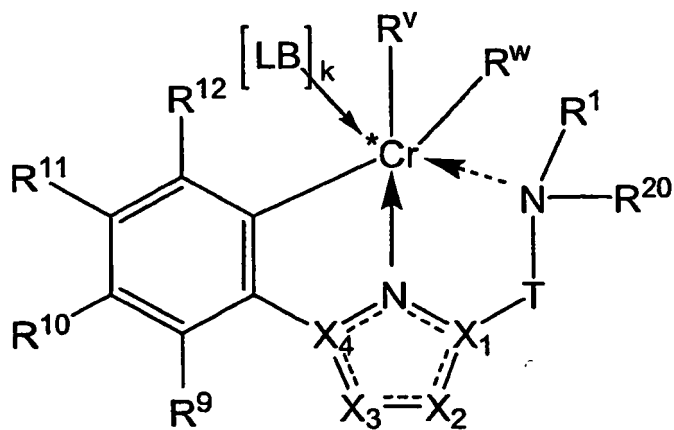
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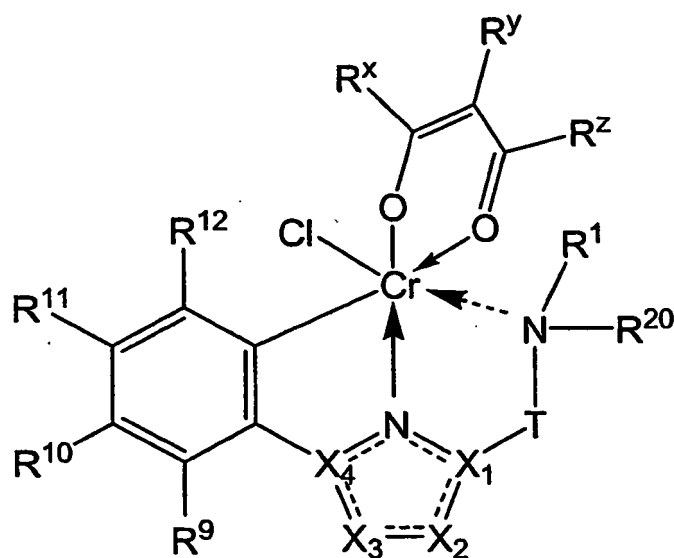
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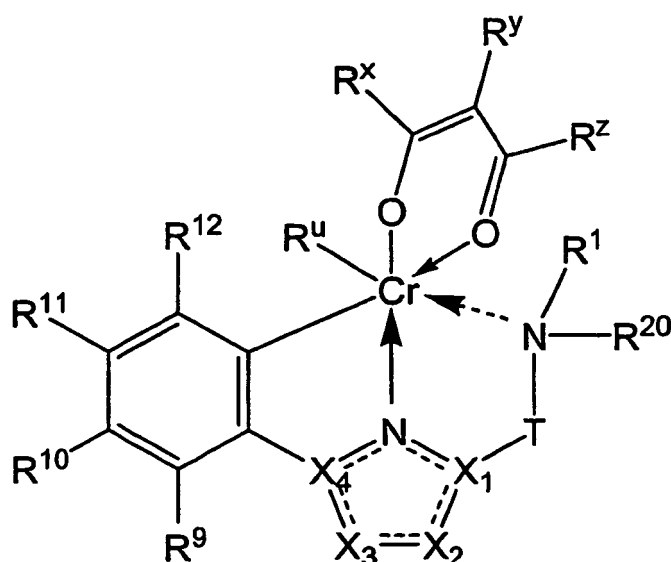


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wherein R¹, R², R³, R⁸, R²⁰, X¹, X², X³, X⁴, n', n'', L, m' and T are as defined above;

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R⁹, R¹⁰, R¹¹, R¹², R¹³, R¹⁴ and R¹⁶, if present, are independently selected from the group consisting of hydrogen, halogen, nitro, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, and optionally two or more R⁹, R¹⁰, R¹¹, R¹², R¹³, R¹⁴ and R¹⁶ groups may be joined to form one or more optionally substituted ring systems;

R^u, R^v, R^w, R^x, R^y and R^z are optionally substituted alkyl, heteroalkyl, aryl, heteroaryl;

E, if present, is a carbon atom that is part of an optionally substituted aryl or heteroaryl ring;

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D, if present, is a ring selected from the group consisting of optionally substituted aryl and heteroaryl;

a dashed arrow indicates that the dative bond is an optional bond which may or may not be present;

LB is a Lewis base;

k = 0 or 1.

[0095] In certain embodiments, where "E" is present, the aryl or heteroaryl ring may be polycyclic.

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[0096] In addition, the catalyst systems of this invention may be combined with other catalysts in a single reactor and/or employed in a series of reactors (parallel or serial).

[0097] The ligands-metal-precursors combinations and the metal ligand complexes, described above, are optionally activated in various ways to yield compositions active for selective ethylene oligomerization. For the purposes of this

patent specification and appended claims, the terms "cocatalyst" and "activator" are used herein interchangeably and are defined to be any compound which can activate any one of the ligands-metal-precursor-combinations and the metal ligand complexes, described above by converting the combination, complex, or composition into a catalytically active species. Non-limiting activators, for example, include alumoxanes, aluminum alkyls, other metal or main group alkyl or aryl compounds, ionizing activators, which may be neutral or ionic, Lewis acids, reducing agents, oxidizing agents, and combinations thereof.

[0098] In one embodiment, alumoxane activators are utilized as an activator in the compositions useful in the invention. Alumoxanes are generally oligomeric compounds containing Al(R*)-O- sub-units, where R* is an alkyl group. Examples of alumoxanes include methylalumoxane (MAO), ethylalumoxane, isobutylalumoxane, and modified methylalumoxanes (MMAO), which include alkyl groups other than methyl such as ethyl, isobutyl, and n-octyl, such as MMAO-3A, PMAO-IP (referring to polymethylalumoxane, improved process, manufactured by Akzo-Nobel and meaning an MAO prepared from a non-hydrolytic process). Alkylalumoxanes and modified alkylalumoxanes are suitable as catalyst activators, particularly when the abstractable ligand of the catalyst is a halide, alkoxide or amide. Mixtures of different alumoxanes and modified alumoxanes may also be used.

[0099] The activator compounds comprising Lewis-acid activators and in particular alumoxanes are specifically characterized by the following general formulae



where R^a, R^b, R^c and R^e are, independently a C₁-C₃₀ alkyl radical, for example, methyl, ethyl, propyl, butyl, pentyl, hexyl, heptyl, octyl, nonyl, decyl, and "p" is an integer from 1 to about 50. Most specifically, R^a, R^b, R^c and R^d are each methyl and "p" is a least 4. When an alkyl aluminum halide or alkoxide is employed in the preparation of the alumoxane, one or more R^a, R^b, R^c or R^e are groups may be halide or alkoxide.

[0100] It is recognized that alumoxane is not a discrete material. An alumoxane is generally a mixture of both the linear and cyclic compounds. A typical alumoxane will contain free trisubstituted or trialkyl aluminum, bound trisubstituted or trialkyl aluminum, and alumoxane molecules of varying degree of oligomerization. Those methylalumoxanes most preferred contain lower levels of trimethylaluminum. Lower levels of trimethylaluminum can be achieved by reaction of the trimethylaluminum with a Lewis base or by vacuum distillation of the trimethylaluminum or by any other means known in the art.

[0101] For further descriptions, see U.S. Pat. Nos. 4,665,208, 4,952,540, 5,041,584, 5,091,352, 5,206,199, 5,204,419, 4,874,734, 4,924,018, 4,908,463, 4,968,827, 5,329,032, 5,248,801, 5,235,081, 5,157,137, 5,103,031 and EP0561476A1, EP0279586B1, EP0516476A1, EP0594218A1 and WO94/10180.

[0102] When the activator is an alumoxane (modified or unmodified), some embodiments select the maximum amount of activator at a 5000-fold molar excess Al/Cr over the catalyst precursor. The minimum preferred activator-to-catalyst-precursor is a 1:1 molar ratio. More specifically, the Al/Cr ratio is from 1000:1 to 100:1.

[0103] Alumoxanes may be produced by the hydrolysis of the respective trialkylaluminum compound. MMAO may be produced by the hydrolysis of trimethylaluminum and a higher trialkylaluminum such as triisobutylaluminum. MMAO's are generally more soluble in aliphatic solvents and more stable during storage. There are a variety of methods for preparing alumoxane and modified alumoxanes, non-limiting examples of which are described in U.S. Pat. Nos. 4,665,208, 4,952,540, 5,091,352, 5,206,199, 5,204,419, 4,874,734, 4,924,018, 4,908,463, 4,968,827, 5,308,815, 5,329,032, 5,248,801, 5,235,081, 5,157,137, 5,103,031, 5,391,793, 5,391,529, 5,693,838, 5,731,253, 5,731,451, 5,744,656, 5,847,177, 5,854,166, 5,856,256 and 5,939,346 and European publications EP0561476A1, EP0279586B1, EP0594218A1 and EP0586665B1, and PCT publications WO94/10180 and WO99/15534. It may be preferable to use a visually clear methylalumoxane. A cloudy or gelled alumoxane can be filtered to produce a clear solution or clear alumoxane can be decanted from the cloudy solution. Another alumoxane is a modified methyl alumoxane (MMAO) cocatalyst type 3A (commercially available from Akzo Chemicals, Inc. under the trade name Modified Methylalumoxane type 3A, covered under patent number U.S. Pat. No. 5,041,584).

[0104] Aluminum alkyl or organoaluminum compounds which may be utilized as activators (or scavengers) include trimethylaluminum, triethylaluminum, triisobutylaluminum, tri-n-hexylaluminum, tri-n-octylaluminum, diisobutylaluminum hydride, ethylaluminum dichloride, diethylaluminum chloride, diethylaluminum ethoxide.

Ionizing Activators

[0105] In some embodiments, the activator includes compounds that may abstract a ligand making the metal complex cationic and providing a charge-balancing non-coordinating or weakly coordinating anion. The term "non-coordinating anion" (NCA) means an anion which either does not coordinate to said cation or which is only weakly coordinated to

said cation thereby remaining sufficiently labile to be displaced by a neutral Lewis base.

[0106] It is within the scope of this invention to use an ionizing or stoichiometric activator, neutral or ionic, such as tri (n-butyl) ammonium tetrakis (pentafluorophenyl) boron, a tris(perfluorophenyl) boron metalloid precursor or a tris(perfluoronaphthyl) boron metalloid precursor, polyhalogenated heteroborane anions (WO98/43983), boric acid (U.S. Pat. No. 5,942,459) or combination thereof. It is also within the scope of this invention to use neutral or ionic activators alone or in combination with alumoxane or modified alumoxane activators.

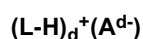
[0107] Examples of neutral stoichiometric activators include tri-substituted boron, tellurium, aluminum, gallium and indium or mixtures thereof. The three substituent groups are each independently selected from alkyls, alkenyls, halogen, substituted alkyls, aryls, arylhalides, alkoxy and halides. In some embodiments, the three groups are independently selected from halogen, mono or multicyclic (including halosubstituted) aryls, alkyls, and alkenyl compounds and mixtures thereof, preferred are alkenyl groups having 1 to 20 carbon atoms, alkyl groups having 1 to 20 carbon atoms, alkoxy groups having 1 to 20 carbon atoms and aryl groups having 3 to 20 carbon atoms (including substituted aryls). In other embodiments, the three groups are alkyls having 1 to 4 carbon groups, phenyl, naphthyl or mixtures thereof. In further embodiments, the three groups are halogenated, specifically fluorinated, aryl groups. In even further embodiments, the neutral stoichiometric activator is tris(perfluorophenyl) boron or tris(perfluoronaphthyl) boron.

[0108] Ionic stoichiometric activator compounds may contain an active proton, or some other cation associated with, but not coordinated to, or only loosely coordinated to, the remaining ion of the ionizing compound. Such compounds are described in European publications EP0570982A1, EP0520732A1, EP0495375A1, EP0500944B1, EP0277003A1 and EP0277004A1, and U.S. Pat. Nos. 5,153,157, 5,198,401, 5,066,741, 5,206,197, 5,241,025, 5,384,299 and 5,502,124 and US 6,143,686.

[0109] Ionic catalysts can be prepared by reacting a Cr compound with some neutral Lewis acids, such as $B(C_6F_5)_3$, which upon reaction with the abstractable ligand (X) of the Cr compound forms an anion, such as $([B(C_6F_5)_3(X)]^-)$, which stabilizes the cationic Cr species generated by the reaction. The catalysts can be prepared with activator components which are ionic compounds or compositions.

[0110] In some embodiments, compounds useful as an activator component in the preparation of the ionic catalyst systems used in the process of this invention comprise a cation, which is optionally a Brønsted acid capable of donating a proton, and a compatible non-coordinating anion which is capable of stabilizing the active catalyst species which is formed when the two compounds are combined and said anion will be sufficiently labile to be displaced by olefinic substrates or other neutral Lewis bases such as ethers, and nitriles. Two classes of compatible non-coordinating anions useful herein have been disclosed in EP0277003A1 and EP0277004A1 published 1988: anionic coordination complexes comprising a plurality of lipophilic radicals covalently coordinated to and shielding a central charge-bearing metal or metalloid core; and, anions comprising a plurality of boron atoms such as carboranes, metallacarboranes and boranes.

[0111] In one preferred embodiment, the stoichiometric activators include a cation and an anion component, and may be represented by the following formula:



where L is a neutral Lewis base; H is hydrogen; $(L-H)^+$ is a Brønsted acid; A^{d-} is a non-coordinating anion having the charge d-; and d is an integer from 1 to 3.

[0112] The cation component, $(L-H)_d^+$ may include Brønsted acids such as protons or protonated Lewis bases or reducible Lewis acids capable of protonating or abstracting a moiety, such as an alkyl or aryl, from the bulky ligand chromium catalyst precursor, resulting in a cationic transition metal species.

[0113] The activating cation $(L-H)_d^+$ may be a Brønsted acid, capable of donating a proton to the transition metal catalytic precursor resulting in a transition metal cation, including ammoniums, oxoniums, phosphoniums, silyliums, and mixtures thereof, specifically ammoniums of methylamine, aniline, dimethylamine, diethylamine, N-methylaniline, diphenylamine, trimethylamine, triethylamine, N,N-dimethylaniline, methyldiphenylamine, pyridine, p-bromo N,N-dimethylaniline, p-nitro-N,N-dimethylaniline, phosphoniums from triethylphosphine, triphenylphosphine, and diphenylphosphine, oxoniums from ethers such as dimethyl ether diethyl ether, tetrahydrofuran and dioxane, sulfoniums from thioethers, such as diethyl thioethers and tetrahydrothiophene, and mixtures thereof. The activating cation $(L-H)_d^+$ may also be a moiety such as silver, tropylium, carbeniums, ferroceniums and mixtures, specifically carboniums and ferroceniums. In one embodiment $(L-H)_d^+$ can be triphenyl carbonium.

[0114] The anion component A^{d-} includes those having the formula $[M^k+Q_n]^{d-}$ wherein k is an integer from 1 to 3; n is an integer from 2-6; n - k = d; M is an element selected from Group 13 of the Periodic Table of the Elements, specifically boron or aluminum, and Q is independently a hydride, bridged or unbridged dialkylamido, halide, alkoxide, aryloxide, hydrocarbyl, substituted hydrocarbyl, halocarbyl, substituted halocarbyl, and halosubstituted-hydrocarbyl radicals, said Q having up to 20 carbon atoms with the proviso that in not more than 1 occurrence is Q a halide. Specifically, each Q is a fluorinated hydrocarbyl group having 1 to 20 carbon atoms, more specifically each Q is a fluorinated aryl group, and most specifically each Q is a pentafluoryl aryl group. Examples of suitable A^{d-} also include diboron compounds as

disclosed in U.S. Pat. No. 5,447,895.

[0115] Illustrative, but not limiting examples of boron compounds which may be used as an activating cocatalyst in the preparation of the improved catalysts of this invention are tri-substituted ammonium salts such as:

5 trimethylammonium tetraphenylborate, triethylammonium tetraphenylborate, tripropylammonium tetraphenylborate, tri(n-butyl)ammonium tetraphenylborate, tri(t-butyl)ammonium tetraphenylborate, N,N-dimethylanilinium tetraphenylborate, N,N-diethylanilinium tetraphenylborate, N,N-dimethyl-(2,4,6-trimethylanilinium) tetraphenylborate, tropillium tetraphenylborate, triphenylcarbenium tetraphenylborate, triphenylphosphonium tetraphenylborate, triethylsilylium tetraphenylborate, benzene(diazonium)tetraphenylborate, trimethylammonium tetrakis(pentafluorophenyl)borate, triethylammonium tetrakis(pentafluorophenyl)borate, tripropylammonium tetrakis(pentafluorophenyl)borate, tri(n-butyl)ammonium tetrakis(pentafluorophenyl)borate, tri(sec-butyl)ammonium tetrakis(pentafluorophenyl)borate, N,N-dimethylanilinium tetrakis(pentafluorophenyl)borate, N,N-diethylanilinium tetrakis(pentafluorophenyl)borate, N,N-dimethyl-(2,4,6-trimethylanilinium) tetrakis(pentafluorophenyl)borate, tropillium tetrakis(pentafluorophenyl)borate, triphenylcarbenium tetrakis(pentafluorophenyl)borate, triphenylphosphonium tetrakis(pentafluorophenyl)borate, triethylsilylium tetrakis(pentafluorophenyl)borate, benzene(diazonium) tetrakis(pentafluorophenyl)borate, trimethylammonium tetrakis-(2,3,4,6-tetrafluorophenyl) borate, triethylammonium tetrakis-(2,3,4,6-tetrafluorophenyl)borate, tripropylammonium tetrakis-(2,3,4,6-tetrafluorophenyl)borate, tri(n-butyl)ammonium tetrakis-(2,3,4,6-tetrafluorophenyl)borate, dimethyl(t-butyl)ammonium tetrakis-(2,3,4,6-tetrafluorophenyl)borate, N,N-dimethylanilinium tetrakis-(2,3,4,6-tetrafluorophenyl)borate, N,N-diethylanilinium tetrakis-(2,3,4,6-tetrafluorophenyl)borate, N,N-dimethyl-(2,4,6-trimethylanilinium) tetrakis-(2,3,4,6-tetrafluorophenyl)borate, tropillium tetrakis-(2,3,4,6-tetrafluorophenyl)borate, triphenylcarbenium tetrakis-(2,3,4,6-tetrafluorophenyl)borate, triphenylphosphonium tetrakis-(2,3,4,6-tetrafluorophenyl)borate, triethylsilylium tetrakis-(2,3,4,6-tetrafluorophenyl)borate, benzene(diazonium) tetrakis-(2,3,4,6-tetrafluorophenyl)borate, trimethylammonium tetrakis(perfluoronaphthyl)borate, triethylammonium tetrakis(perfluoronaphthyl)borate, tripropylammonium tetrakis(perfluoronaphthyl)borate, tri(n-butyl)ammonium tetrakis(perfluoronaphthyl)borate, tri(t-butyl)ammonium tetrakis(perfluoronaphthyl)borate, N,N-dimethylanilinium tetrakis(perfluoronaphthyl)borate, N,N-diethylanilinium tetrakis(perfluoronaphthyl)borate, N,N-dimethyl-(2,4,6-trimethylanilinium) tetrakis(perfluoronaphthyl)borate, tropillium tetrakis(perfluoronaphthyl)borate, triphenylcarbenium tetrakis(perfluoronaphthyl)borate, triphenylphosphonium tetrakis(perfluoronaphthyl)borate, triethylsilylium tetrakis(perfluoronaphthyl)borate, benzene(diazonium) tetrakis(perfluoronaphthyl)borate, trimethylammonium tetrakis(perfluorobiphenyl)borate, triethylammonium tetrakis(perfluorobiphenyl)borate, tripropylammonium tetrakis(perfluorobiphenyl)borate, tri(n-butyl)ammonium tetrakis(perfluorobiphenyl)borate, tri(t-butyl)ammonium tetrakis(perfluorobiphenyl)borate, N,N-dimethylanilinium tetrakis(perfluorobiphenyl)borate, N,N-diethylanilinium tetrakis(perfluorobiphenyl)borate, N,N-dimethyl-(2,4,6-trimethylanilinium) tetrakis(perfluorobiphenyl)borate, tropillium tetrakis(perfluorobiphenyl)borate, triphenylcarbenium tetrakis(perfluorobiphenyl)borate, triphenylphosphonium tetrakis(perfluorobiphenyl)borate, triethylsilylium tetrakis(perfluorobiphenyl)borate, benzene(diazonium) tetrakis(perfluorobiphenyl)borate, trimethylammonium tetrakis(3,5-bis(trifluoromethyl)phenyl)borate, triethylammonium tetrakis(3,5-bis(trifluoromethyl)phenyl)borate, tripropylammonium tetrakis(3,5-bis(trifluoromethyl)phenyl)borate, tri(n-butyl)ammonium tetrakis(3,5-bis(trifluoromethyl)phenyl)borate, tri(t-butyl)ammonium tetrakis(3,5-bis(trifluoromethyl)phenyl)borate, N,N-dimethylanilinium tetrakis(3,5-bis(trifluoromethyl)phenyl)borate, N,N-diethylanilinium tetrakis(3,5-bis(trifluoromethyl)phenyl)borate, N,N-dimethyl-(2,4,6-trimethylanilinium) tetrakis(3,5-bis(trifluoromethyl)phenyl)borate, tropillium tetrakis(3,5-bis(trifluoromethyl)phenyl)borate, triphenylcarbenium tetrakis(3,5-bis(trifluoromethyl)phenyl)borate, triphenylphosphonium tetrakis(3,5-bis(trifluoromethyl)phenyl)borate, triethylsilylium tetrakis(3,5-bis(trifluoromethyl)phenyl)borate, benzene(diazonium) tetrakis(3,5-bis(trifluoromethyl)phenyl)borate, and dialkyl ammonium salts such as: di-(i-propyl)ammonium tetrakis(pentafluorophenyl)borate, and dicyclohexylammonium tetrakis(pentafluorophenyl)borate; and additional tri-substituted phosphonium salts such as tri(o-tolyl)phosphonium tetrakis(pentafluorophenyl)borate, and tri(2,6-dimethylphenyl)phosphonium tetrakis(pentafluorophenyl)borate.

45 **[0116]** Most specifically, the ionic stoichiometric activator (L-H)_d⁺ (A^{d-}) is N,N-dimethylanilinium tetra(perfluorophenyl)borate, N,N-dimethylanilinium tetrakis(perfluoronaphthyl)borate, N,N-dimethylanilinium tetrakis(perfluorobiphenyl)borate, N,N-dimethylanilinium tetrakis(3,5-bis(trifluoromethyl)phenyl)borate, triphenylcarbenium tetrakis(perfluoronaphthyl)borate, triphenylcarbenium tetrakis(perfluorobiphenyl)borate, triphenylcarbenium tetrakis(3,5-bis(trifluoromethyl)phenyl)borate, or triphenylcarbenium tetra(perfluorophenyl)borate.

50 **[0117]** Other examples of preferred ionizing activators include, HNMe(C₁₈H₃₇)₂⁺B(C₆F₅)₄⁻; HNPh(C₁₈H₃₇)₂⁺B(C₆F₅)₄⁻ and ((4-n-Bu-C₆H₄)NH(n-hexyl))₂⁺B(C₆F₅)₄⁻ and ((4-n-Bu-C₆H₄)NH(n-decyl))₂⁺B(C₆F₅)₄⁻. Specific preferred (L^{*}-H)⁺ cations are N,N-dialkylanilinium cations, such as HNMe₂Ph⁺, substituted N,N-dialkylanilinium cations, such as (4-n-Bu-C₆H₄)NH(n-C₆H₁₃)₂⁺ and (4-n-Bu-C₆H₄)NH(n-C₁₀H₂₁)₂⁺ and HNMe(C₁₈H₃₇)₂⁺. Specific examples of anions are tetrakis(3,5-bis(trifluoromethyl)phenyl)borate and tetrakis(pentafluorophenyl)borate.

55 **[0118]** In one embodiment, activation methods using ionizing ionic compounds not containing an active proton but capable of producing an active oligomerization catalyst are also contemplated. Such methods are described in relation to metallocene catalyst compounds in EP0426637A1, EP0573403A1 and U.S. Patent No. 5,387,568.

[0119] The process can also employ cocatalyst compounds or activator compounds that are initially neutral Lewis

acids but form a cationic metal complex and a noncoordinating anion, or a zwitterionic complex upon reaction with the compounds of this invention. For example, tris(pentafluorophenyl) boron or aluminum may act to abstract a hydrocarbyl or hydride ligand to yield a cationic metal complex and stabilizing noncoordinating anion.

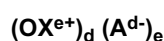
[0120] In some embodiments, ionizing activators may be employed as described in Köhn et al. (J. Organomet. Chem., 683, pp 200-208, (2003)) to, for example, improve solubility.

[0121] In another embodiment, the aforementioned cocatalyst compounds can also react with the compounds to produce a neutral, uncharged catalyst capable of selective ethylene oligomerization. For example, Lewis acidic reagents such as, for example, alkyl or aryl aluminum or boron compounds, can abstract a Lewis basic ligand such as, for example, THF or Et₂O, from a compound yielding a coordinatively unsaturated catalyst capable of selective ethylene oligomerization.

[0122] When the cations of noncoordinating anion precursors are Brønsted acids such as protons or protonated Lewis bases (excluding water), or reducible Lewis acids such as ferrocenium or silver cations, or alkali or alkaline earth metal cations such as those of sodium, magnesium or lithium, the activator-to-catalyst-precursor molar ratio may be any ratio, however, useful ratios can be from 1000:1 to 1:1.

[0123] Combinations of two or more activators may also be used in the practice of this invention.

[0124] Another suitable ion forming, activating cocatalyst comprises a salt of a cationic oxidizing agent and a noncoordinating, compatible anion characterized by the general formula:



where OX^{e+} is a cationic oxidizing agent having a charge of e+; e is an integer from 1 to 3; d is an integer from 1 to 3, and Ad⁻ is as previously defined. Examples of cationic oxidizing agents include: ferrocenium, hydrocarbyl-substituted ferrocenium, Ag⁺, or Pb⁺². Preferred embodiments of A^{d-} are those anions previously defined with respect to the Brønsted acid containing activators, especially tetrakis(pentafluorophenyl)borate.

Group 13 Reagents, Divalent Metal Reagents, and Alkali Metal Reagents

[0125] Other general activators or compounds useful in an oligomerization reaction may be used. These compounds may be activators in some contexts, but may also serve other functions in the reaction system, such as alkylating a metal center or scavenging impurities. These compounds are within the general definition of "activator," but are not considered herein to be ion-forming activators. These compounds include a group 13 reagent that may be characterized by the formula G¹³R⁵⁰_{3-p}D_p where G¹³ is selected from the group consisting of B, Al, Ga, In, and combinations thereof, p is 0, 1 or 2, each R⁵⁰ is independently selected from the group consisting of hydrogen, halogen, and optionally substituted alkyl, alkenyl, alkynyl, heteroalkyl, heteroalkenyl, heteroalkynyl, aryl, heteroaryl, and combinations thereof, and each D is independently selected from the group consisting of halogen, hydrogen, alkoxy, aryloxy, amino, mercapto, alkylthio, arylthio, phosphino and combinations thereof.

[0126] In other embodiments, the group 13 activator is an oligomeric or polymeric alumoxane compound, such as methylalumoxane and the known modifications thereof. See, for example, Barron, "Alkylalumoxanes, Synthesis, Structure and Reactivity", pp. 33-67 in *Metallocene-Based Polyolefins: Preparation, Properties and Technology*, J. Schiers and W. Kaminsky (eds.), Wiley Series in Polymer Science, John Wiley & Sons Ltd., Chichester, England, 2000, and references cited therein.

[0127] In other embodiments, a divalent metal reagent may be used that is characterized by the general formula M'R⁵⁰_{2-p}D_p, and p' is 0 or 1 in this embodiment and R⁵⁰ and D are as defined above. M' is the metal and is selected from the group consisting of Mg, Ca, Sr, Ba, Zn, Cd, Cu and combinations thereof.

[0128] In still other embodiments, an alkali metal reagent may be used that is defined by the general formula M^{iv}R⁵⁰ and in this embodiment R⁵⁰ is as defined above, and M^{iv} is the alkali metal and is selected from the group consisting of Li, Na, K, Rb, Cs and combinations thereof. Additionally, hydrogen and/or silanes may be used in the catalytic composition or added to the polymerization system. Silanes may be characterized by the formula SiR⁵⁰_{4-q}D_q where R⁵⁰ is defined as above, q is 1, 2, 3 or 4 and D is as defined above, with the proviso that at least one D is hydrogen.

[0129] Non-limiting examples of Group 13 reagents, divalent metal reagents, and alkali metal reagents useful as activators for the catalyst compounds described above include methyl lithium, butyl lithium, phenyl lithium, dihexylmercury, butylmagnesium, diethylcadmium, benzylpotassium, diethyl zinc, tri-n-butyl aluminum, diisobutyl ethylboron, diethylcadmium, di-n-butyl zinc and tri-n-amyl boron, and, in particular, the aluminum alkyls, such as trihexyl-aluminum, triethylaluminum, trimethylaluminum, and triisobutyl aluminum, diisobutyl aluminum bromide, diethylaluminum chloride, ethylaluminum dichloride, isobutyl boron dichloride, methyl magnesium chloride, ethyl beryllium chloride, ethyl calcium bromide, diisobutyl aluminum hydride, methyl cadmium hydride, diethyl boron hydride, hexylberyllium hydride, dipropylboron hydride, octylmagnesium hydride, butyl zinc hydride, dichloroboron hydride, di-bromo-aluminum hydride and bromocadmium hydride. Other Group 13 reagents, divalent metal reagents, and alkali metal reagents useful as activators for the catalyst compounds described above are known to those in the art, and a more complete discussion of these compounds may be found in U.S. Pat. Nos. 3,221,002 and 5,093,415.

[0130] Other activators include those described in PCT publication WO98/07515 such as tris(2,2',2"-nonafluorobiphenyl) fluoroaluminate. Combinations of activators are also contemplated by the invention, for example, alumoxanes and ionizing activators in combinations, see for example, EP0573120B1, PCT publications WO94/07928 and WO95/14044 and U.S. Pat. Nos. 5,153,157 and 5,453,410.

[0131] Other suitable activators are disclosed in WO98/09996, which describes activating bulky ligand metallocene catalyst compounds with perchlorates, periodates and iodates including their hydrates. WO98/30602 and WO98/30603, describe the use of lithium (2,2'-bisphenyl-ditrimethylsilicate)•4THF as an activator for a bulky ligand metallocene catalyst compound. WO99/18135, describes the use of organo-boron-aluminum activators. EP0781299B1 describes using a silylium salt in combination with a non-coordinating compatible anion. Also, methods of activation such as using radiation (see EP0615981B1, electro-chemical oxidation, are also contemplated as activating methods for the purposes of rendering the chromium complexes or compositions active for the selective oligomerization of olefins. Other activators or methods are described in for example, U.S. Pat. Nos. 5,849,852, 5,859,653 and 5,869,723 and WO98/32775, WO99/4246 (dioctadecylmethylammonium-bis(tris(pentafluorophenyl)borane) benzimidazole).

[0132] Additional optional activators include metal salts of noncoordinating or weakly coordinating anions, for example where the metal is selected from Li, Na, K, Ag, Ti, Zn, Mg, Cs, and Ba.

[0133] It is within the scope of this invention that metal-ligand complexes and or ligand-metal-precursor-combinations can be combined with one or more activators or activation methods described above. For example, a combination of activators has been described in U.S. Pat. Nos. 5,153,157 and 5,453,410, EP0573120B1, and PCT publications WO94/07928 and WO95/14044. These documents all discuss the use of an alumoxane in combination with an ionizing activator.

[0134] In one embodiment, the molar ratio of metal (from the metal-ligand-complex or the ligand-metal-precursor-combination) to activator (specifically Cr. activator, specifically Cr: Al or Cr:B) can range from 1:1 to 1:5000. In another embodiment, the molar ratio of metal to activator employed can range from 1:1 to 1:500. In another embodiment, the molar ratio of metal to activator employed can range from 1:1 to 1:50. In another embodiment, the molar ratio of chromium to activator employed can range from 1:1 to 1:500. In another embodiment, the molar ratio of chromium to activator employed can range from 1:1 to 1:50.

[0135] In embodiments where more than one activator is used, the order in which the activators are combined with the metal-ligand-complex or the ligand-metal-precursor-combination may be varied.

[0136] In some embodiments, the process of the invention relates to the oligomerization, and more specifically the trimerization and/or tetramerization of ethylene. The ligand-metal-precursor-combinations, metal-ligand-complexes, and/or catalyst systems of this invention are particularly effective at oligomerizing and specifically trimerizing and/or tetramerizing ethylene to form 1-hexene and/or 1-octene.

[0137] In other embodiments, this invention relates to the oligomerization and more specifically the trimerization and/or tetramerization of α -olefins or co-oligomerization of ethylene with α -olefins. The trimerization of α -olefins is described in Köhn et al., *Angew. Chem. Int. Ed.*, 39 (23), pp 4337-4339 (2000).

[0138] Very generally, oligomerization can be carried out in the Ziegler-Natta or Kaminsky-Sinn methodology, including temperatures from -100°C to 300°C and pressures from atmospheric to 3000 atmospheres (303,900 kPa). Suspension, solution, slurry, gas phase, or high-pressure oligomerization processes may be employed with the catalysts and compounds of this invention. Such processes can be run in a batch, semi-batch, or continuous mode. Examples of such processes are well known in the art.

[0139] Suitable solvents for oligomerization are non-coordinating, inert liquids. Examples include straight and branched-chain hydrocarbons such as isobutane, butane, pentane, isopentane, hexane, isohexane, heptane, octane, dodecane, and mixtures thereof; cyclic and alicyclic hydrocarbons such as cyclohexane, cycloheptane, methylcyclohexane, methylcycloheptane, and mixtures thereof; perhalogenated hydrocarbons such as perfluorinated C₄₋₁₀ alkanes, chlorobenzene, and aromatic and alkylsubstituted aromatic compounds such as benzene, toluene, mesitylene, and xylene. Suitable solvents also include liquid olefins which may act as monomers or comonomers including ethylene, propylene, 1-butene, 1-hexene, 1-pentene, 3-methyl-1-pentene, 4-methyl-1-pentene, 1-octene, and 1-decene. Mixtures of the foregoing are also suitable.

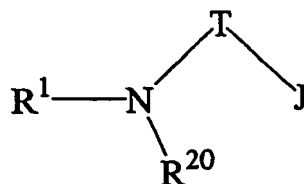
[0140] Other additives that are useful in an oligomerization reaction may be employed, such as scavengers, promoters, modifiers, reducing agents, oxidizing agents, dihydrogen, aluminum alkyls, or silanes. For example, Jolly et al. (*Organometallics*, 16, pp 1511-1513 (1997)) has reported the use of magnesium as a reducing agent for Cr compounds that were synthesized as models for intermediates in selective ethylene oligomerization reactions.

[0141] In some useful embodiments, the activator (such as methylalumoxane or modified methylalumoxane-3A) is combined with the metal-ligand-complex or the ligand-metal-precursor-combination immediately prior to introduction into the reactor. Such mixing may be achieved by mixing in a separate tank then swift injection into the reactor, mixing in-line just prior to injection into the reactor. It has been observed that in some instances, a short activation time is very useful. Likewise in-situ activation, where the catalyst system components are injected separately into the reactor, with or without monomer, and allowed to combine within the reactor directly is also useful in the practice of this invention. In

some embodiments, the catalyst system components are allowed to contact each other for 30 minutes or less, prior to contact with monomer, alternately for 5 minutes or less, alternately for 3 minutes or less, alternately for 1 minute or less. [0142] In another embodiment, the present invention relates to methods of producing oligomers of olefins, catalysts, ligands used to prepare the catalyst and catalyst compositions as described in the following paragraphs.

[0143] In a first embodiment, the method includes reacting an olefin with a catalyst wherein the oligomerization reaction has a selectivity of at least 70 mole percent for oligomer, and wherein the catalyst is formed from the combination of:

(1) a ligand characterized by the following general formula:



wherein R^1 and R^{20} are each independently selected from the group consisting of hydrogen and optionally substituted hydrocarbyl, heteroatom containing hydrocarbyl and silyl, provided that R^1 or R^{20} do not equal T-J, where T-J is as given by the general formula above and defined below;

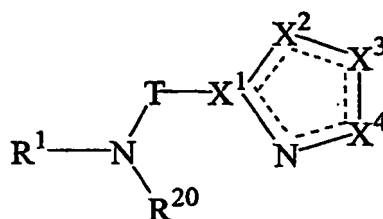
T is a bridging group of the general formula $-(T'R^2R^3)-$, where T' is selected from the group consisting of carbon and silicon, R^2 and R^3 are independently selected from the group consisting of hydrogen, halogen, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, provided that two or more R^2 and/or R^3 groups may be joined together to form one or more optionally substituted ring systems having from 3-50 non-hydrogen atoms;

J is an optionally substituted five-membered heterocycle, containing at least one nitrogen atom as part of the ring; with the further proviso that J contains at least two, but not more than four, heteroatoms.

(2) a metal precursor compound characterized by the general formula $Cr(L)_n$ where each L is independently selected from the group consisting of halide, alkyl, substituted alkyl, cycloalkyl, substituted cycloalkyl, heteroalkyl, substituted heteroalkyl heterocycloalkyl, substituted heterocycloalkyl, aryl, substituted aryl, heteroaryl, substituted heteroaryl, alkoxy, aryloxy, hydroxy, boryl, silyl, amino, amine, hydrido, allyl, diene, seleno, phosphino, phosphine, ether, thioether, carboxylates, thio, 1,3-dionates, oxalates, carbonates, nitrates, sulfates, ethers, thioethers and combinations thereof, wherein two or more L groups may be combined in a ring structure having from 3 to 50 non-hydrogen atoms; n is 1, 2, 3, 4, 5, or 6; and

(3) optionally, one or more activators.

[0144] In a second embodiment of the first method, the ligand is characterized by the following general formula:



wherein R^1 , R^{20} , and T are described above; and X^1 is nitrogen or $-C(R^8)_{n'}$, X^2 , X^3 , and X^4 are selected from the group consisting of oxygen, sulfur, $-C(R^8)_{n'}$, $-N(R^8)_{n''}$, and provided that X^1 is $-C(R^8)_{n'}$ or at least one of X^2 , X^3 , or X^4 is $-C(R^8)_{n'}$, each n' is 1 or 2 and each n'' is 0 or 1; and,

each R^8 is independently selected from the group consisting of hydrogen, halogen, nitro, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, and optionally two or more R^1 , R^{20} , R^2 , R^3 , and R^8 groups may be joined to form one or more optionally substituted ring systems.

[0145] In a third embodiment of the first method, R^1 and R^{20} are each independently selected from hydrogen and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, silyl and combinations thereof.

[0146] In a fourth embodiment, R^1 and R^{20} are each independently selected from hydrogen and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, silyl and combinations thereof for the second embodiment.

[0147] In a fifth embodiment, R^1 is hydrogen and R^{20} is selected from optionally substituted alkyl, heteroalkyl, cycloalkyl, heterocycloalkyl, silyl and combinations thereof for the second embodiment.

[0148] In a sixth through ninth embodiment of the first method, the ligand includes one or more of B1, B2, B3, C1, C2, C3, C4, C5, D1, D2, D3, D4, and/or E1.

[0149] In a tenth embodiment, the method is of any one of the first nine embodiments, wherein the activator is an alumoxane, which may optionally be used in any combination with group 13 reagents, divalent metal reagents, or alkali metal reagents.

[0150] In an eleventh embodiment, the method is of any one of the first nine embodiments, wherein the activator is a neutral or ionic stoichiometric activator, which may optionally be used in any combination with group 13 reagents, divalent metal reagents, or alkali metal reagents.

[0151] In a twelfth embodiment, the method is any of any one of the first nine embodiments wherein the activator is selected from the group consisting of modified methylalumoxane (MMAO), methylalumoxane (MAO), trimethylaluminum (TMA), triisobutyl aluminum (TIBA), diisobutylaluminumhydride (DIBAL), polymethylalumoxane-IP (PMAO), triphenyl-carbonium tetrakis(perfluorophenyl)borate, N,N-dimethyl-anilinium tetrakis(perfluorophenyl)borate N,N-di(n-decyl)-4-n-butyl-anilinium tetrakis(perfluorophenyl)borate, and mixtures thereof.

[0152] In a thirteenth embodiment, the method is any one of the first nine embodiments wherein the metal precursor is selected from the group consisting of $(\text{THF})_3\text{CrMeCl}_2$, $(\text{THF})_3\text{CrCl}_3$, $(\text{Mes})_3\text{Cr}(\text{THF})$, $[\{\text{TFA}\}_2\text{Cr}(\text{OEt}_2)]_2$, $(\text{THF})_3\text{Cr}(\eta^2\text{-}2,2\text{-biphenyl})\text{Br}$, $(\text{THF})_3\text{CrPh}_3$ and mixtures thereof.

[0153] In a fourteenth embodiment of the first method the olefin is a C_2 to C_{12} olefin.

[0154] In a fifteenth embodiment of the first method the olefin is a C_2 to C_8 olefin.

[0155] In a sixteenth embodiment of the first method the olefin is ethylene.

[0156] In a seventeenth embodiment, the process produces a trimer or a tetramer of the olefin by the sixteenth embodiment.

[0157] In an eighteenth embodiment, the process produces 1-hexene by the seventh embodiment.

[0158] In a nineteenth embodiment, the process produces 1-octene by the eighteenth embodiment.

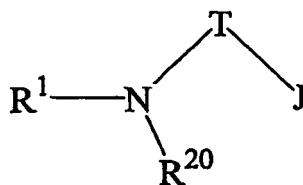
[0159] In a twentieth embodiment, the process produces a mixture of 1-hexene and 1-octene by the sixteenth embodiment.

[0160] In a twenty first embodiment, the reaction occurs in a hydrocarbon solvent in the first method.

[0161] In a twenty second embodiment, the reaction occurs in an aliphatic hydrocarbon solvent in the twenty first embodiment.

[0162] A twenty third embodiment provides a composition comprising:

(1) a ligand characterized by the following general formula:

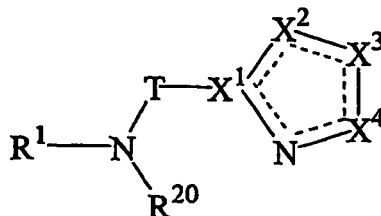


wherein R^1 and R^{20} are each independently selected from the group consisting of hydrogen and optionally substituted alkyl, provided that R^1 or R^{20} do not equal T-J, where T-J is as given by the general formula above and defined below; T is a bridging group of the general formula $-(\text{T}^i\text{R}^2\text{R}^3)-$, where T^i is selected from the group consisting of carbon and silicon, R^2 and R^3 are independently selected from the group consisting of hydrogen, halogen, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, provided that two or more R^2 and/or R^3 groups may be joined together to form one or more optionally substituted ring systems having from 3-50 non-hydrogen atoms; J is an optionally substituted five-membered heterocycle, containing at least one nitrogen atom as part of the ring; with the further proviso that J contains at least two but not more than four, heteroatoms.

(2) a metal precursor compound characterized by the general formula $\text{Cr}(\text{L})_n$ where each L is independently selected from the group consisting of halide, alkyl, substituted alkyl, cycloalkyl, substituted cycloalkyl, heteroalkyl, substituted heteroalkyl, heterocycloalkyl, substituted heterocycloalkyl, aryl, substituted aryl, heteroaryl, substituted heteroaryl, alkoxy, aryloxy, hydroxy, boryl, silyl, amino, amine, hydrido, allyl, diene, seleno, phosphino, phosphine, ether,

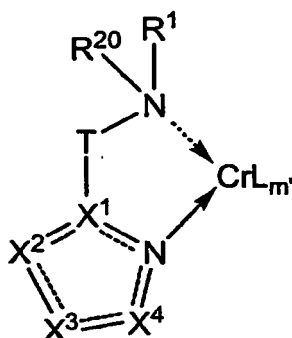
thioether, carboxylates, thio, 1,3-dionates, oxalates, carbonates, nitrates, sulfates, ethers, thioethers and combinations thereof, wherein two or more L groups may be combined in a ring structure having from 3 to 50 non-hydrogen atoms; n is 1, 2, 3, 4, 5, or 6; and
 (3) optionally, one or more activators.

[0163] A twenty fourth embodiment provides that the ligand is characterized by the following general formula:



wherein R^1 , R^{20} , and T are described above; and X^1 is nitrogen or $-C(R^8)_{n''}$, X^2 , X^3 , and X^4 are selected from the group consisting of oxygen, sulfur, $-C(R^8)_{n''}$, $-N(R^8)_{n''}$, and provided that X^1 is $-C(R^8)_{n''}$ or at least one of X^2 , X^3 , or X^4 is $-C(R^8)_n$, each n' is 1 or 2 and each n'' is 0 or 1; and,
 each R^8 is independently selected from the group consisting of hydrogen, halogen, nitro, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, and optionally two or more R^1 , R^{20} , R^2 , R^3 , and R^8 groups may be joined to form one or more optionally substituted ring systems in the twenty third embodiment.

[0164] A twenty fifth embodiment provides a complex characterized by the following general formula:



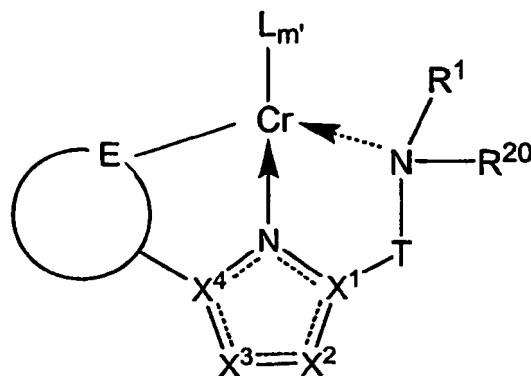
wherein R^1 and R^{20} are each independently selected from the group consisting of hydrogen and optionally substituted alkyl, heteroalkyl, cycloalkyl, heterocycloalkyl, aryl, heteroaryl, silyl and combinations thereof;
 X^1 is nitrogen or $-C(R^8)_{n''}$, X^2 , X^3 and X^4 are independently selected from the group consisting of oxygen, sulfur, $-C(R^8)_{n''}$ or $-N(R^8)_{n''}$, where each n' is 1 or 2, and each n'' is 0 or 1, and each R^8 is independently selected from the group consisting of hydrogen, halogen, nitro, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof;
 T is a bridging group of the general formula $-(T'R^2R^3)-$, where T' is selected from the group consisting of carbon and silicon, R^2 and R^3 are independently selected from the group consisting of hydrogen, halogen, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, provided that two or more R^2 and/or R^3 groups may be joined together to form one or more optionally substituted ring systems having from 3-50 non-hydrogen atoms; any combination of two or more R^1 , R^2 , R^3 , and/or R^8 groups may be joined together to form one or more optionally substituted fused ring systems;
 each L is independently selected from the group consisting of halide, alkyl, substituted alkyl, cycloalkyl, substituted cycloalkyl, heteroalkyl, substituted heteroalkyl heterocycloalkyl, substituted heterocycloalkyl, aryl, substituted aryl, heteroaryl, substituted heteroaryl, alkoxy, aryloxy, hydroxy, boryl, silyl, amino, amine, hydrido, allyl, diene, seleno, phosphino, phosphine, ether, thioether, carboxylates, thio, 1,3-dionates, oxalates, carbonates, nitrates, sulfates, ethers, thioethers and combinations thereof, wherein two or more L groups may be combined in a ring structure having from 3 to 50 non-hydrogen atoms;

m' is 1, 2 or 3; and

a dashed arrow indicates that the dative bond is an optional bond which may or may not be present.

[0165] A twenty sixth embodiment provides that R^8 is optionally substituted aryl or heteroaryl, and R^8 and M are optionally joined to form a metallocycle in the twenty fifth embodiment.

[0166] A twenty seventh embodiment provides a metal complex characterized by the following general formula:



wherein R^1 and R^{20} are each independently selected from the group consisting of hydrogen and optionally substituted alkyl heteroalkyl, cycloalkyl, heterocycloalkyl, aryl, heteroaryl, silyl and combinations thereof;

X^1 is nitrogen or $-C(R^8)_{n''}$, X^2 , X^3 and X^4 are independently selected from the group consisting of oxygen, sulfur, $-C(R^8)_{n''}$ or $-N(R^8)_{n''}$, where each n' is 1 or 2, and each n'' is 0 or 1, and each R^8 is independently selected from the group consisting of hydrogen, halogen, nitro, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof;

T is a bridging group of the general formula $-(T'R^2R^3)-$, where T' is selected from the group consisting of carbon and silicon, R^2 and R^3 are independently selected from the group consisting of hydrogen, halogen, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, provided that two or more R^2 and/or R^3 groups may be joined together to form one or more optionally substituted ring systems having from 3-50 non-hydrogen atoms; any combination of two or more R^1 , R^2 , R^3 , and/or R^8 groups may be joined together to form one or more optionally substituted fused ring systems.

each L is independently selected from the group consisting of halide, alkyl, substituted alkyl, cycloalkyl, substituted cycloalkyl, heteroalkyl, substituted heteroalkyl heterocycloalkyl, substituted heterocycloalkyl, aryl, substituted aryl, heteroaryl, substituted heteroaryl, alkoxy, aryloxy, hydroxy, boryl, silyl, amino, amine, hydrido, allyl, diene, seleno, phosphino, phosphine, ether, thioether, carboxylates, thio, 1,3-dionates, oxalates, carbonates, nitrates, sulfates, ethers, thioethers and combinations thereof, wherein two or more L groups may be combined in a ring structure having from 3 to 50 non-hydrogen atoms; m' is 1, 2 or 3;

E is a carbon atom that is part of an optionally substituted aryl or heteroaryl ring; and

a dashed arrow indicates that the dative bond is an optional bond which may or may not be present.

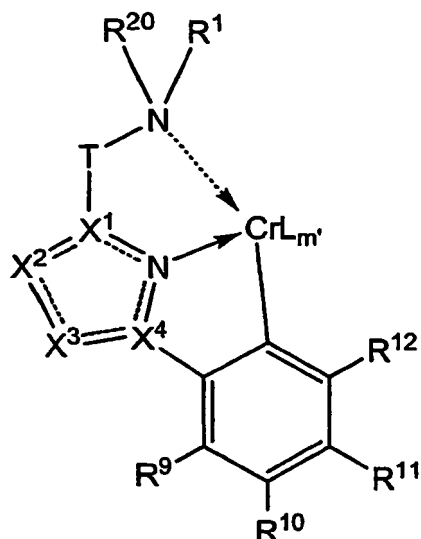
[0167] A twenty eighth embodiment provides that the complex is characterized by the formula:

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wherein R^1 , R^{20} , X^1 , X^2 , X^3 , X^4 , L , T and m' are as defined above; R^9 , R^{10} , R^{11} , and R^{12} are each independently selected from the group consisting of hydrogen, halogen, nitro, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, provided that optionally, two or more of R^9 , R^{10} , R^{11} and R^{12} may be joined to form one or more optionally substituted fused ring systems; and a dashed arrow indicates that the dative bond is an optional bond which may or may not be present in the twenty seventh embodiment.

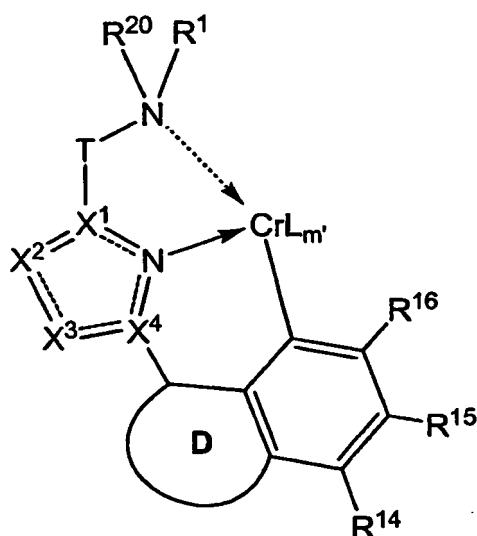
[0168] A twenty ninth embodiment provides that the complex is characterized by the formula:

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wherein R^1 , R^{20} , and wherein said catalyst is selected from one of the twenty fifth through twenty ninth embodiments, and optionally, an activator.

[0169] A thirty first embodiment provides that the olefin is ethylene in the thirtieth embodiment.

[0170] A thirty second embodiment provides that the thirty first embodiment process produces a trimer or a tetramer of the olefin.

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[0171] A thirty third embodiment provides that the thirty second embodiment process produces 1-hexene.

[0172] A thirty fourth embodiment provides that the thirty second embodiment process produces 1-octene.

[0173] A thirty fifth embo, X^1 , X^2 , X^3 , X^4 , L , T and m' are as defined above;

R^{14} , R^{15} and R^{16} are each independently selected from the group consisting of hydrogen, halogen, nitro, and optionally

substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, provided that optionally, two or more of R¹⁴, R¹⁵ and R¹⁶ may be joined to form one or more optionally substituted fused ring systems;

D is a ring selected from the group consisting of optionally substituted aryl and heteroaryl; and

a dashed arrow indicates that the dative bond is an optional bond which may or may not be present in the twenty seventh embodiment.

[0174] A thirtieth embodiment provides a method of producing oligomers of olefins, comprising reacting an olefin with a catalyst, wherein said oligomerization reaction has a selectivity of at least 70 mole percent for oligomerization. A method of producing oligomers of olefins, comprising reacting an olefin with a catalyst wherein said oligomerization reaction produces two oligomers wherein the combined selectivity of the two oligomers sums to at least 70 mole percent, and wherein said catalyst is comprised the metal complexes is selected from one of the twenty third through the twenty ninth embodiments, and optionally, an activator.

[0175] A thirty sixth embodiment provides that the process of the thirty fifth embodiment produces a mixture of 1-hexene and 1-octene.

[0176] A thirty eighth embodiment provides that the process of the thirty sixth embodiment occurs in a hydrocarbon solvent.

[0177] A thirty eighth embodiment provides that the process of the thirty seventh embodiment occurs in an aliphatic hydrocarbon solvent.

EXAMPLES

[0178] General: All air sensitive procedures were performed under a purified argon or nitrogen atmosphere in a Vacuum Atmospheres or MBraun glove box. All solvents used were anhydrous, de-oxygenated and purified according to known techniques (see for example, D. D. Perrin & W. L. F. Armarego Purification of Laboratory Chemicals, 3rd Ed., (Pergamon Press: New York, 1988)). All ligands and metal precursors were prepared according to procedures known to those of skill in the art, e.g., under inert atmosphere conditions. Ethylene oligomerization experiments were carried out in a parallel pressure reactor, described in U.S. Patents 6,306,658, 6,455,316 and 6,489,168, and in U.S. Application No. 09/177,170, filed October 22, 1998, WO 00/09255, and a parallel batch reactor with in situ injection capability, as described in WO 04/060550, and U.S. Application No. 2004/0121448.

[0179] Quantitative analysis of the liquid olefin products was performed using an automated Agilent 6890 Dual Channel Gas Chromatograph fitted with 2 Flame Ionization Detectors. The liquid olefin products were first separated using RT-x1 columns (1.25 m length x 0.25 mm thickness x 1 μm width; manufactured by Restek and spooled into module by RVM Scientific) and quantified by flame ionization detection by comparison with calibration standards. Cyclooctane was used as an internal standard. Samples were loaded onto the columns from an 8 x 12 array of 1 mL glass vials using a CTC HTS PAL LC-MS autosampler purchased from LEAPTEC. Polyethylene yields were determined using a Bohdan model BA-100 automated weighing module.

Ligand Synthesis

Example 2. Thiazole-Amine Ligand Synthesis

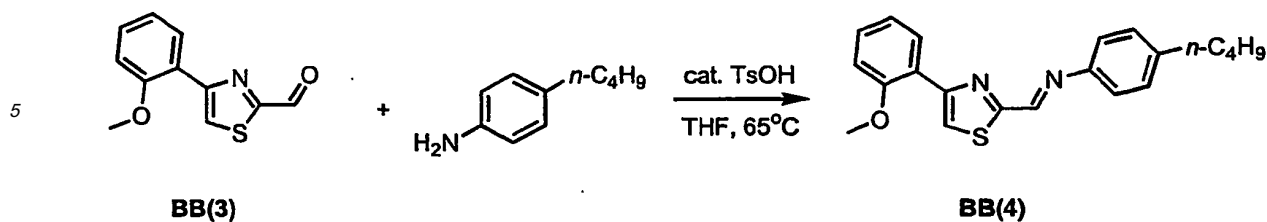
[0180] Thiazole-amine ligands can be prepared according to the general procedure outlined in Scheme 2, above, in which an R⁸-substituted thiazole-aldehyde is prepared from the corresponding bromo-aldehyde in a coupling reaction. The resultant substituted thiazole-amine aldehyde is then reacted with a primary amine to form the intermediate imine, which is then reacted with a nucleophile to provide the corresponding amine.

Example 2. Thiazol-2-yl)-alkyl Amine Ligand Synthesis.

Example 2a

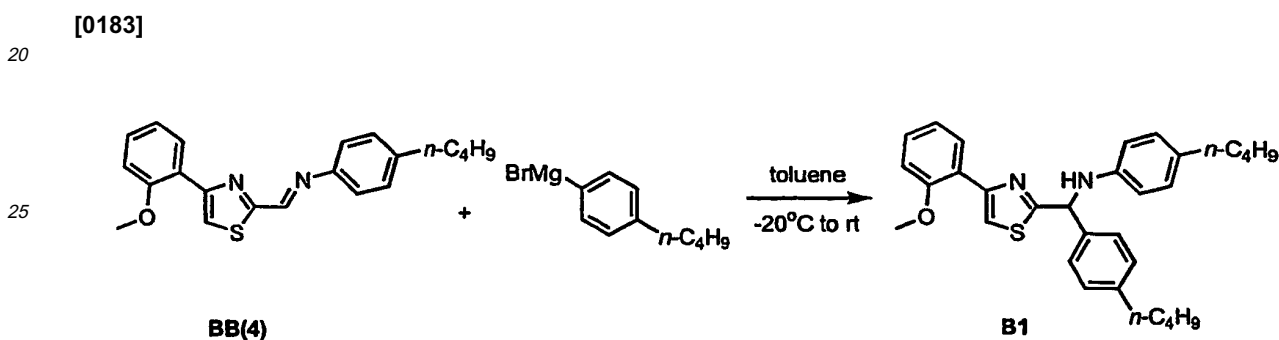
Step 1

[0181]



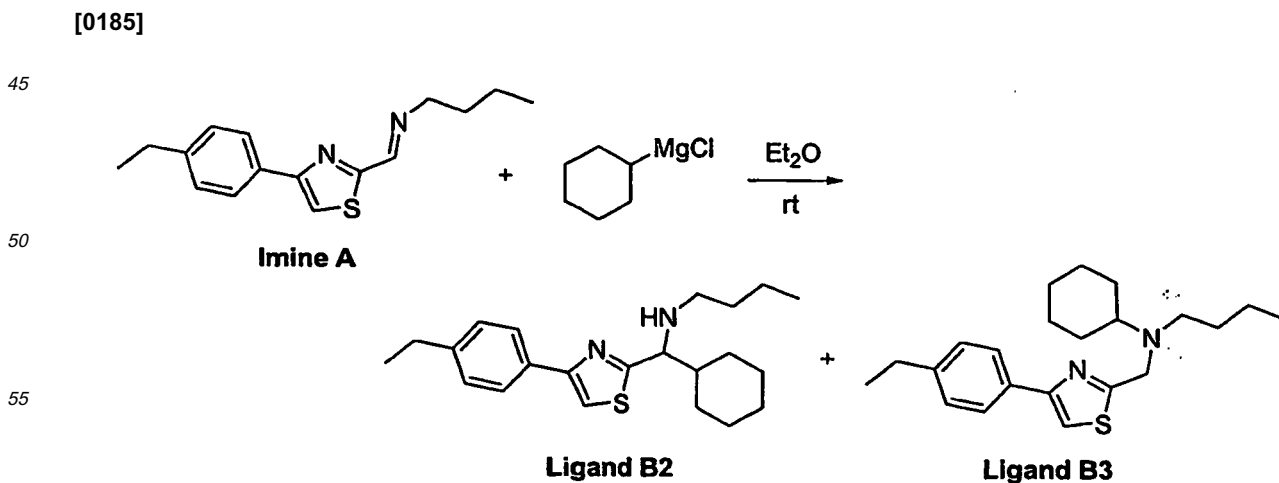
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[0182] The thiazole-amine aldehyde BB(3) (110 mg, 0.50 mmol), 4-butylaniline (83 μL , 0.53 mmol), and TsOH (catalytic amount, ca. 5 mol %) were combined in THF (4 mL) over 3A molecular sieves. The reaction was heated at 65°C for 3h. The molecular sieves were removed by filtration and the reaction solution was concentrated by rotary evaporation then dried under vacuum to give 1.75 mg of imine BB(4) as an orange semi-solid. The BB(4) imine was used without further purification.

Step 2



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[0184] 4-*n*-Butylphenylmagnesium bromide (2.0 mL, 0.5 M in THF) was concentrated under a stream of N_2 to remove THF. The Grignard reagent was taken up in Et_2O (2 mL) and added dropwise to a solution of the imine BB(4) (175 mg, 0.50 mmol) in Et_2O (4 mL) at -20°C under N_2 . Additional Et_2O (2 mL) was used to transfer the Grignard reagent, and the reaction was stirred at room temperature overnight. The reaction was quenched with sat. NH_4Cl (aq.) and the layers were separated. The organic layer was washed with sat. NH_4Cl (aq.), H_2O , brine, dried over Na_2SO_4 , and purified by silica gel chromatography eluting with hexanes / CH_2Cl_2 = 2 / 1, providing 118 mg (49% yield) of the desired ligand B1, as shown above in Step 2, as a yellow viscous oil.

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Example 2b.

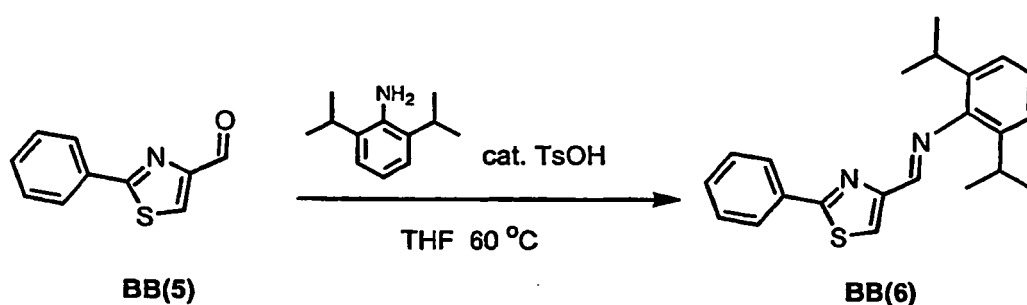


[0186] The reaction was set up in the glove box. To a solution of **imine A** (69 mg, 0.25 mmol, prepared using the method described above) in Et₂O (3 mL) was added cyclohexylmagnesium chloride (139 μ L, 0.28 mmol, 2.0 M in Et₂O) at rt. The resulting dark green reaction was stirred overnight at rt. The reaction mixture was quenched with sat. NH₄Cl aqueous solution. The organic layer was then washed with brine, dried over Na₂SO₄, and concentrated under reduced pressure. The crude product was purified by silica gel chromatography (Hexanes : EtOAc = 20 : 1) to obtain 26 mg of **Ligand B2** (29%) as a yellow oil and 25 mg of **Ligand B3** (28%) as a yellow oil.

Example 2b. (Thiazol-4-yl)-alkyl Amine Ligand Synthesis.

Step 1

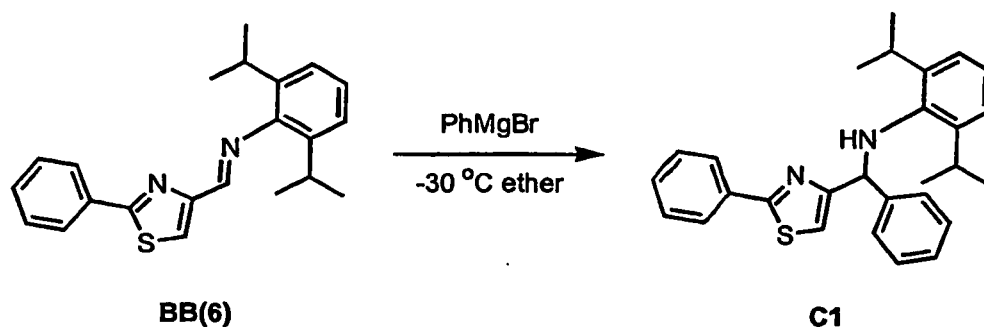
[0187]



[0188] To a solution of 2-phenyl-1,3-thiazole-4-carboxaldehyde (**BB(5)**, 1.00 g, 5.29 mmol) in 30 mL of dry THF was added 2,6-diisopropylaniline (95%, 5.53 mmol, 1.10 mL) and a catalytic amount of TsOH (about 15 mg) at room temperature. To this reaction mixture was then added oven-dried 3 angstrom molecular sieves (about 5 g). The resultant mixture was vigorously stirred for 15 min at 60 °C. The reaction mixture was then filtered and concentrated under reduced pressure. The crude product **BB(6)** was then used directly in the next step.

Step 2

[0189]



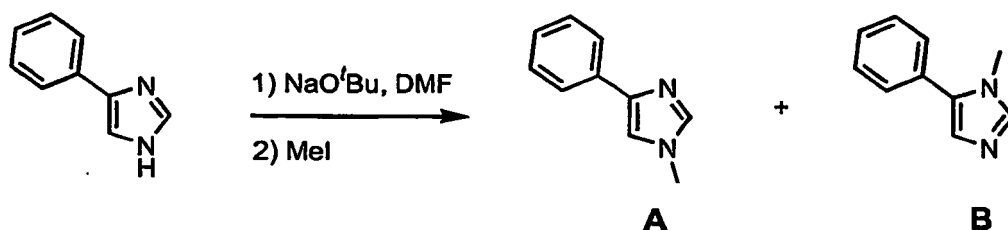
[0190] The crude product, **BB(6)**, from Step 1 was redissolved in 60 mL of dry ether. To this solution was added PhMgBr (13.2 mol, 3.0 M, 4.4 mL) at -30 °C. The reaction mixture was allowed to warm up to room temperature and stirred overnight. The reaction was quenched with a saturated NaCl solution (50 mL), and extracted with EtOAc (2 \times 30 mL). The organic layers were then combined and dried with Na₂SO₄. The reaction product was filtered, concentrated under reduced pressure, and then purified by column chromatography (1:9, Ether:Hexanes) to give 1.30 g of the desired product **C1**. Ligands **C1-C5**, as illustrated in Fig. 2, were either prepared using the procedures detailed above, or through variations to these procedures that are apparent to one of ordinary skill in the art.

Example 3: Imidazole-Amine Ligand Synthesis.

Example 3a

Step 1

[0191]



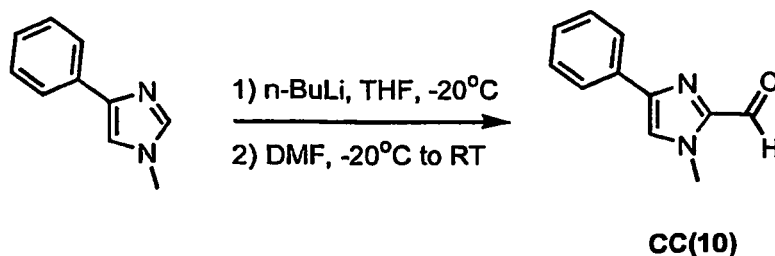
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[0192] A DMF (7 mL) solution of 4-Phenylimidazole (1.0 g, 6.94 mmol) and NaO^tBu (733 mg, 7.63 mmol) was stirred under N₂ at room temperature for ca. 15 min. before adding iodomethane (0.475 mL, 7.63 mmol). A white precipitate formed after addition of iodomethane, and the resulting reaction suspension was stirred overnight at room temperature. DMF was removed under reduced pressure and the crude reaction mixture was taken up in CH₂Cl₂. The resulting CH₂Cl₂ suspension was filtered to remove insoluble salts then washed twice with H₂O, once with brine, dried over Na₂SO₄, and purified by silica gel chromatography using EtOAc to elute isomer **A** and EtOAc / MeOH = 10 / 1 to elute isomer **B**. Isolated 775 mg (71% yield) of isomer **A** as a white solid and 229 mg (21 % yield) of isomer **B** as a white solid.

Step 2

[0193]



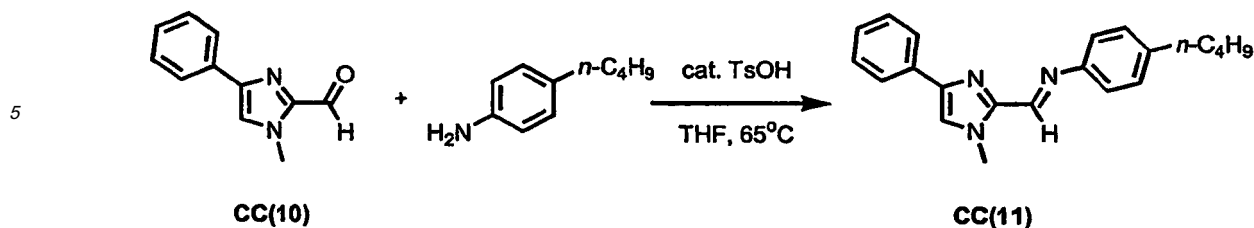
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[0194] A solution of n-BuLi (0.87 mL, 1.39 mmol) was added dropwise to a solution of N-methyl-4-phenylimidazole (200 mg, 1.26 mmol) in THF (10 mL) at -20°C under N₂. The resulting orange solution was kept at -20°C for 2 hours before adding DMF (0.147 mL, 1.90 mmol). The reaction was allowed to warm slowly to room temperature and stirred overnight. THF was removed by rotary evaporation and the crude reaction mixture was taken up in Et₂O. The Et₂O solution was washed with sat NH₄Cl (aq.), H₂O, brine, and then dried over Na₂SO₄. The crude product was dissolved in CH₂Cl₂ and passed through a small plug of silica gel. Isolated 216 mg (92% yield) of the desired aldehyde CC(10) as an off-white solid.

Step 3

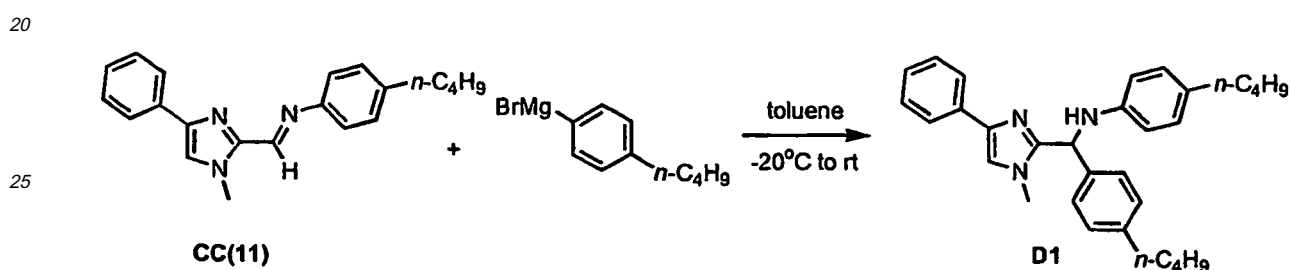
[0195]



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 [0196] The aldehyde (93 mg, 0.50 mmol), 4-n-Butylaniline (83 μL , 0.53 mmol), and TsOH (ca. 5 mol %) were combined in THF (4 mL) over 3A molecular sieves. The reaction was heated at 65°C for 3h. The molecular sieves were removed by filtration and the reaction solution was concentrated by rotary evaporation then dried under vacuum to give 151 mg of imine CC(11) as an orange solid. The imine CC(11) was used without further purification.

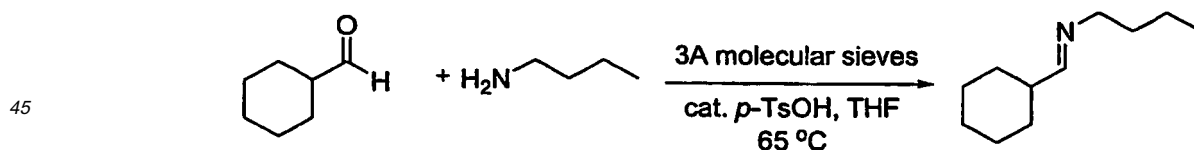
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Step 4

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 [0197]



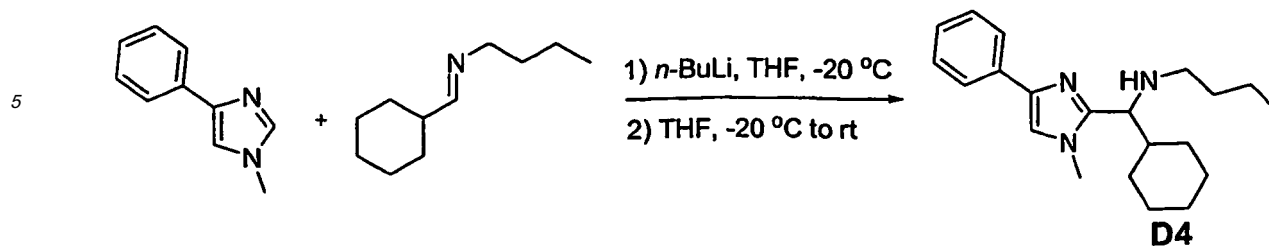
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 [0198] 4-n-Butylphenylmagnesium bromide (2.0 mL, 0.5 M in THF) was concentrated under a stream of N_2 to remove the THF. The Grignard reagent was taken up in toluene (2 mL) and added dropwise to a solution of the imine CC(11) (151 mg, 0.48 mmol) in toluene (6 mL) at -20°C under N_2 . The reaction was stirred at room temperature overnight. The reaction was then quenched with sat. NH_4Cl (aq.) and the layers were separated. The organic layer was washed with sat. NH_4Cl (aq.), H_2O , brine, dried over Na_2SO_4 , and purified by silica gel chromatography eluting with hexanes / EtOAc =10/1, providing 167 mg (78% yield) of the desired imidazole-amine ligand D1 as a viscous yellow oil. Ligands D1-D3, as illustrated in Fig. 3, were prepared using the procedures detailed above, or through variations to these procedures that are apparent to one of ordinary skill in the art.

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Example 3b



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 [0199] To a solution of cyclohexanecarboxaldehyde (209 mg, 1.86 mmol) and n-butylamine (203 μL , 2.05 mmol) in THF (5 mL) was added 3A molecular sieves and catalytic amount *p*-TsOH. The reaction mixture was heated at 65°C for 4 hr. After cooling, the reaction mixture was filtered and concentrated under reduced pressure. The crude imine was used directly in the next reaction.

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[0200] The reaction was set up in the glove box. *n*-BuLi (312 μ L, 0.50 mmol, 1.6 M in hexanes) was added dropwise to a solution of A phenyl-imidazole (79 mg, 0.50 mmol) in THF (3 mL) at -20 $^{\circ}$ C. After 2 hr at -20 $^{\circ}$ C, a solution of imine from previous reaction in THF (2 mL), which has been cooled to -20 $^{\circ}$ C, was added to the reaction mixture. The reaction was allowed to warm up to rt and stirred overnight. The reaction was then quenched with sat. NH_4Cl aqueous solution and extracted with Et_2O (3X 10 mL). The organic layers were combined and dried over Na_2SO_4 , purified by silica gel chromatography (Hexanes : EtOAc = 10 : 1) to obtain 106 mg of D4 (65%) as a faint yellow viscous oil.

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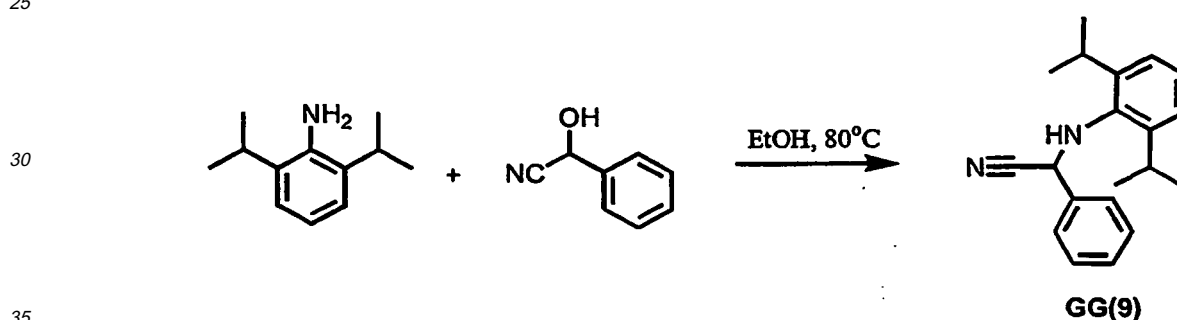
Example 4: Oxadiazole-Amine Ligand Synthesis

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Step 1

[0201]

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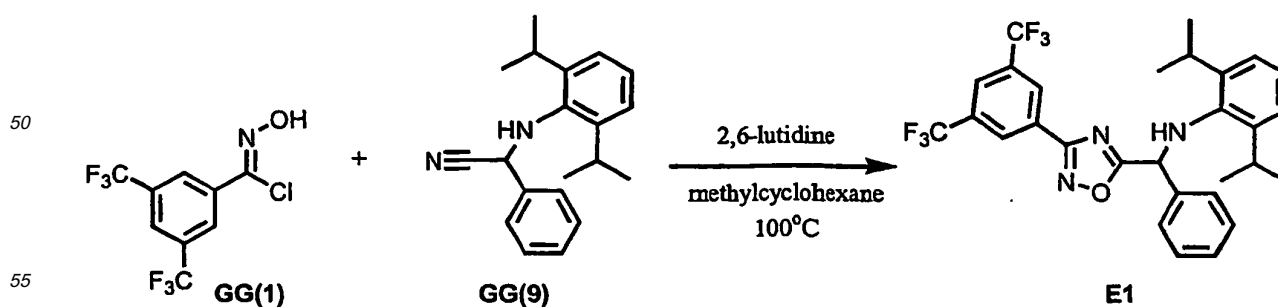
[0202] Mandelonitrile (0.80 mL, 6.72 mmol), 2,6-diisopropylaniline (0.63 mL, 3.35 mmol), and EtOH (8.0 mL) were heated at 80 $^{\circ}$ C in a sealed scintillation vial for 18 hours. The resulting product was purified by flash chromatography on silica gel eluting with hexanes / ethyl acetate = 20 / 1, providing 506mg, 52% yield, of product GG(9) as a light yellow oil.

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Step 2

[0203]

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[0204] A reaction flask was charged under N_2 with GG(9) (0.30 mmol), GG(1) (0.90 mmol), methylcyclohexane (6

mL), and 2,6-lutidine (0.90 mmol). The reaction was stirred at room temperature for 30 minutes then heated at 100°C for 18 hours. After cooling to room temperature, the reaction was filtered to remove insoluble material. The filtrate was concentrate and purified by flash chromatography on silica gel, resulting in the desired ligand E1.

5 Example 5. Selective Ethylene Oligomerization Examples in a 96-well Format.

5a. General Protocols

[0205] Ethylene oligomerization reactions were performed in a 96-well format using 1 mL glass vials arranged in an 8 x 12 array within an aluminum block. Reagents were added from stock solutions or slurries to the 1 mL vials using a Cavro liquid handling robot driven by Symyx software, see, for example, U.S. Patent No. 6,507,945, or a manual hand pipettor. The vials contained parylene coated stir-bars and were weighed prior to their use in screening (described below). Solutions of a parent array of desired ligands were transferred to arrays of glass vials (0.3 μmol of each ligand) and the solvent was then removed from the ligand array using a nitrogen or argon stream. The resultant ligand array was then contacted with a suitable chromium precursor, an activator (or combination of activators) and pressurized with ethylene within a parallel batch reactor with *in situ* injection capability. Specific details are described below. The parallel batch reactor is described in WO04/060550, and U.S. Application No. 2004/0121448.

Chromium Precursor Synthesis

[0206] (THF)₃CrMeCl₂ was prepared as described in Nishimura, K. et al. J. Organomet. Chem. 37, pp 317-329 (1972). The compound [(TFA)₂Cr(OEt₂)₂]₂ has been previously described in Cotton, F. A. et al. Inorg. Chem. 17, pp 176-186 (1978), but was prepared by a different method described below. (THF)₃CrPh₃ was prepared as described in Herwig, W. and Zeiss, H. J. Am. Chem. Soc. 81, pp 4798-4801 (1959). (Mes)₃Cr(THF) was prepared as described in Stolze, G. J. Organomet. Chem. 6, pp 383-388 (1966). (Mes)CrCl(THF)₂ was prepared as described by Stolze, G. et al. J. Organomet. Chem. 7, 301-310 (1967). All other Cr reagents were purchased from commercial sources.

Preparation of [(TFA)₂Cr(OEt₂)₂]₂

[0207] To a mixture of 1.00 g of CrCl₂ (8.14 mmol) and 1.96 g of LiTFA (16.28 mmol) was added 20 mL of diethyl ether. The pale green suspension was stirred for 15 h producing a deep violet supernatant with some traces of pale green solids. The suspension was reduced to dryness under a stream of argon and then was further dried *in vacuo* for about 5 minutes. The solids were then extracted with 40 mL of hexane and filtered, and were then further extracted twice with 20 mL of hexane and filtered. The filtrates were combined and reduced to dryness under a stream of argon, producing a deep purple, free-flowing crystalline solid. Isolated yield: 1.96 g.

Stock Solutions

[0208] Stock solution concentrations were as follows:

Chromium Precursors

[0209] **For Complexations in Toluene:** (THF)₃CrMeCl₂ (0.01 M in toluene), (Mes)₃Cr(THF) (0.01 M in toluene), [(TFA)₂Cr(OEt₂)₂]₂ (0.005 M in toluene).

[0210] **For Complexations in THF:** (THF)₃CrPh₃ (0.005 M in THF), (THF)₃CrMeCl₂ (0.005 M in THF), (Mes)₃Cr(THF) (0.005 M in THF), [(TFA)₂Cr(OEt₂)₂]₂ (0.005 M in THF).

Activators/Group 13 Reagents

[0211] Solutions of activators and group 13 reagents were prepared in toluene, n-heptane, or n-dodecane, depending on the choice of solvent for the selective ethylene oligomerization reaction (see Table 1). Alumoxanes were supplied by Akzo Chemical Inc., Chicago, IL. MMAO-3A/AIR₃, PMAO-IP/AIP₃, and SJ2BF₂₀/AIR₃ mixtures were prepared within an hour prior to addition to the ligand-chromium precursor composition. Stock solutions were as follows:

[0212] MMAO-3A: 0.30 M plus 0.195 M cyclooctane as an internal standard).

[0213] MMAO-3A/TMA: 0.150 M MMAO-3A, 0.0375 M TMA plus 0.195 M cyclooctane as an internal standard.

[0214] PMAO-IP/TMA: 0.150 M PMAO-IP, 0.0375 M TMA plus 0.195 M cyclooctane as an internal standard.

[0215] MMAO-3A/TIBA: 0.150 M MMAO-3A, 0.0375 M TIBA plus 0.195 M cyclooctane as an internal standard.

[0216] SJ2BF₂₀/TMA: 0.0015 M SJ2BF₂₀, 0.0375 M TMA plus 0.195 M cyclooctane as an internal standard.

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[0217] SJ2BF₂₀/TIBA: 0.0015 M SJ2BF₂₀, 0.0375 M TIBA plus 0.195 M cyclooctane as an internal standard.

[0218] 5b. *In Situ* Preparation and Screening of Ligand-Chromium Compositions

Method 1: Toluene Room Temperature Complexation, Toluene Screening.

[0219] The ligand array (0.3 μmol of each ligand) was first contacted with toluene (ca. 30 μL per well) and then toluene solutions of the desired chromium precursor (ca. 30 μL per well, 0.3 μmol) were added. The resultant mixtures were stirred for a period of 1 hour at ambient temperature in the presence of 100-150 psi (0.67-1.03 MPa) of ethylene. The array was then treated with a stock solution of the appropriate activator (or activator mixture, 200 μL per well, contact time of ≤ 5 minutes), and placed into the parallel batch reactor and stirred at 50°C under 150 psi (1.03 MPa) of ethylene for 1 hour.

Method 2: Toluene 75°C Complexation, Toluene Screening.

[0220] The ligand array (0.3 μmol of each ligand) was first contacted with toluene (ca. 30 μL per well) and then toluene solutions of the desired chromium precursor (ca. 30 μL per well, 0.3 μmol) were added. The resultant mixtures were stirred for a period of 30 minutes at 75°C in presence of 100-150 psi (0.67-1.03 MPa) of ethylene. The array was then cooled to room temperature and treated with a stock solution of the appropriate activator (or activator mixture, 200 μL per well, contact time of ≤5 minutes), and placed into the parallel batch reactor and stirred at 50°C under 150 psi (1.03MPa) of ethylene for 1 hour.

Method 3: THF Room Temperature Complexation, Toluene Screening.

[0221] The ligand array (0.3 μmol of each ligand) was contacted with THF solutions of the chromium complexes (ca. 60 μL per well, 0.3 μmol) and stirred at room temperature for a period of 2 hours (in the absence of ethylene). The THF was removed by directing a stream of nitrogen or argon over each well in the array. 60 μL of toluene was then added to each well in the array, which was subsequently stirred under 100-150 psi (0.67-1.03 MPa) of ethylene for 15 minutes. The array was then treated with a stock solution of the appropriate activator (or activator mixture, 200 μL per well, contact time of ≤5 minutes), and placed into the parallel batch reactor and stirred at 50°C under 150 psi (1.03MPa) of ethylene for 1 hour.

Method 4: Toluene 75°C Complexation, Dodecane Screening.

[0222] The procedure is identical to that described for method 2 above except that, following the complexation step, the toluene was removed by directing a stream of nitrogen or argon over each well in the array. 60 μL of n-heptane or n-dodecane was then added to each well in the array, which was then stirred under 100-150 psi (0.67-1.03 MPa) of ethylene for 15 minutes. The array was then treated with a stock solution of the appropriate activator (or activator mixture, 200 μL per well, contact time of ≤5 minutes), and placed into the parallel batch reactor and stirred at 50°C under 150 psi (1.03 MPa) of ethylene for 1 hour.

Method 5: THF Room Temperature Complexation, Dodecane Screening.

[0223] The procedure is identical to that described for method 3, except that following the THF removal, each well of the array was treated with 60 μL of n-dodecane and then stirred under 100-150 psi (0.67-1.03 MPa) of ethylene for 15 minutes. The array was then treated with a stock solution of the appropriate activator (or activator mixture, 200 μL per well, contact time of ≤5 minutes), and placed into the parallel batch reactor and stirred at 50°C under 150 psi (1.03 MPa) of ethylene for 1 hour.

Method 6: THF 50°C Complexation, Dodecane Screening.

[0224] The ligand array (0.3 μmol of each ligand) was contacted with THF solutions of the chromium complexes (60 μL per well, 0.3 μmol) and stirred at 50°C for a period of 1 hour (in the absence of ethylene). The array was then cooled to room temperature, whereupon the THF was removed by directing a stream of nitrogen or argon over each well in the array. Each well of the array was subsequently treated with 60 μL of n-dodecane and was stirred under 100-150 psi (0.67-1.03 MPa) of ethylene for 15 minutes. The array was then treated with a stock solution of the appropriate activator (or activator mixture, 200 μL per well, contact time of ≤5 minutes), and placed into the parallel batch reactor and stirred at 50°C under 150 psi (1.03 MPa) of ethylene for 1 hour.

Method 7: Isolated Chromium-Ligand Composition from Ligand A4 and CrMeCl₂(THF)₃, Toluene or Dodecane Screening.

5 [0225] A solution of CrMeCl₂(THF)₃ (28.1 mg, 0.0793 mmol, 0.5 mL toluene) was added to a solution of Ligand A4 (30.0 mg, 0.0793 mmol, 0.5 mL toluene) at ambient temperature. After 15-20 minutes, a beige solid precipitated from solution. The mixture was allowed to stand for 12 hours. The mixture was filtered, and the isolated beige solid was washed with 2 x 0.5 mL toluene. The isolated solid was dissolved in THF, and the THF was removed under a stream of nitrogen. The solid was dried *in vacuo* for 30 minutes (isolated yield, 29 mg). A 0.005 M solution/slurry was prepared with the isolated solid in either toluene or n-dodecane. 60 μL of the toluene or n-dodecane isolated complex solution/slurry was then added to each well in the array. The resultant mixtures were stirred for a period of 5 minutes at ambient temperature in the presence of 100-150 psi of ethylene. The array was then treated with a stock solution of the appropriate activator (or activator mixture, 200 μL per well, contact time of ≤5 minutes), and placed into the parallel batch reactor and stirred at 50°C under 150 psi of ethylene for 1 hour.

Method 8: Isolated Chromium-Ligand Composition from Ligand A4 and CrCl₃(THF)₃, Toluene or Dodecane Screening.

20 [0226] To a mixture of 30.0 mg (0.08 mmol) CrCl₃(THF)₃ and 30.3 mg (0.08 mmol) ligand A4 was added 2 mL of CH₂Cl₂. The reaction mixture became a violet-blue solution almost immediately and was stirred for 2 hours at room temperature. The volatiles were then removed by directing a stream of nitrogen over the solution and the blue-grey residues were dried *in vacuo* for 2 hours (isolated yield: 43 mg). A 0.005 M solution/slurry was prepared with the isolated solid in either toluene or n-dodecane. 60 μL of the toluene or n-dodecane isolated complex solution/slurry was then added to wells in a microtiter plate array of 1 mL glass vials and the resultant mixtures were stirred for a period of 15 minutes at ambient temperature in the presence of 100-150 psi of ethylene. The array was then treated with a stock solution of the appropriate activator (or activator mixture, 200 μL per well, contact time of ≤5 minutes), and placed into the parallel batch reactor and stirred at 50°C under 150 psi of ethylene for 1 hour.

Method 9: Toluene 25°C Complexation, Heptane Screening.

30 [0227] The procedure is identical to that described for method 1 above except that, following the complexation step, the toluene was removed by directing a stream of nitrogen or argon over each well in the array. 60 μL of n-heptane was then added to each well in the array, which was then stirred under 100-150 psi (0.67-1.03 MPa) of ethylene for 15 minutes. The array was then treated with a stock solution of the appropriate activator (or activator mixture, 200 μL per well, contact time of ≤5 minutes), and placed into the parallel batch reactor and stirred at 50°C under 150 psi (1.03 MPa) of ethylene for 1 hour.

Method 10: THF 50°C Complexation, Toluene Screening.

40 [0228] The ligand array (0.3 μmol of each ligand) was contacted with THF solutions of the chromium complexes (60 μL per well, 0.3 μmol) and stirred at 50°C for a period of 1 hour (in the absence of ethylene). The array was then cooled to room temperature, whereupon the THF was removed by directing a stream of nitrogen or argon over each well in the array. Each well of the array was subsequently treated with 60 μL of Toluene and was stirred under 100-150 psi (0.67-1.03 MPa) of ethylene for 15 minutes. The array was then treated with a stock solution of the appropriate activator (or activator mixture, 200 μL per well, contact time of ≤5 minutes), and placed into the parallel batch reactor and stirred at 50°C under 150 psi (1.03 MPa) of ethylene for 1 hour.

5c. Product Analysis.

50 [0229] After 1 hour of reaction, the parallel batch reactor was depressurized and the array was removed. The array of vials was then transferred to a room temperature aluminum block, and to each vial was added ca. 200 μL of toluene followed by 30-50 μL of water. The vials were stirred and then topped off with toluene to bring the total volume to ca. 800 μL. A Teflon sheet and rubber gasket were placed over the top of the array and an aluminum cover was screwed on the top to seal the array. The array was then mechanically agitated and centrifuged at 1500 rpm for 10 minutes before analyzing the composition of each well using Gas Chromatography with a Flame Ionization Detector (e.g. the GC-FID technique). Following the GC analysis of the array, the volatiles were removed under vacuum centrifuge and the vials were weighed in order to determine the yield of solid product. The calculated catalyst and cocatalyst residues were then subtracted from the weight to give the yield of polyethylene produced. Table 1 a presents selected results from the selective ethylene oligomerization reactions performed in 96-well formats. In Table 1 a, 1-hexene selectivity is shown

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as a percentage and is defined as $100 \times [\text{micromoles of 1-hexene}] / [\text{sum of micromoles of } C_6\text{-}C_{16} \text{ olefins (excluding dodecene when dodecane was used as solvent)}]$.

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Table 1a:

Example	Ligand (0.3 μmol)	Chromium Precursor (0.3 μmol)	Method	Solvent	Reactor Temp (°C)	Activation method and mol equivalents versus Cr	μmol catalyst	μmol 1- hexene produced	1-hexene Selectivity	mg polyethylene produced
23	D1	[(TFA) ₂ Cr (OEt ₂) ₂]	1	Toluene	50	100 MMAO- 3A/25 TIBA	0.3	66	90	2
24	D1	(THF) ₃ CrMeCl ₂	1	Toluene	50	100 MMAO- 3A/25 TIBA	0.3	35	91	1
25	D2	[(TFA) ₂ Cr (OEt ₂) ₂]	1	Toluene	50	100 MMAO- 3A/25 TIBA	0.3	55	80	2
26	D2	(Mes) ₃ Cr(THF)	1	Toluene	50	100 MMAO- 3A/25 TIBA	0.3	41	81	5
	B1	[(TFA) ₂ Cr (OEt ₂) ₂]	1	Toluene	50	100 MMAO- 3A/25 TIBA	0.3	128	86	2
28	C1	[(TFA) ₂ Cr (OEt ₂) ₂]	1	Toluene	50	200 MMAO- 3A	0.3	90	88	10
29	C2	[(TFA) ₂ Cr (OEt ₂) ₂]	6	Dodecane	50	100 MMAO- 3A/25 TIBA	0.3	57	87	6
30	C3	[(TFA) ₂ Cr (OEt ₂) ₂]	5	Dodecane	50	100 MMAO- 3A/25 TIBA	0.3	54	75	4
31	C4	[(TFA) ₂ Cr (OEt ₂) ₂]	6	Dodecane	50	100 MMAO- 3A/25 TIBA	0.3	34	82	3
32	E1	(THF) ₃ CrMeCl ₂	1	Toluene	50	100 MMAO- 3A/25 TIBA	0.3	35	90	10
33	E1	[(TFA) ₂ Cr (OEt) ₂]	1	Toluene	50	100 MMAO- 3A/25 TIBA	0.3	35	78	8
34	B3	(THF) ₃ CrMeCl ₂	4	Heptane	50	200 MMAO- 3A	0.3	20	98	2

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[0230] Table 1 b presents selected results from the selective ethylene oligomerization reactions performed in 96-well formats. In Table 1b, 1-hexene selectivity is shown as a percentage and is defined as $100 \times [\text{micromoles of 1-hexene}] / [\text{sum of micromoles of } C_6\text{-}C_{16} \text{ olefins}]$, 1-octene selectivity is shown as a percentage and is defined as $100 \times [\text{micromoles of 1-octene}] / [\text{sum of micromoles of } C_6\text{-}C_{16} \text{ olefins}]$, and {1-hexene + 1-octene} selectivity is shown as a percentage and is defined as $100 \times [(\text{micromoles of 1-hexene}) + (\text{micromoles of 1-octene})] / [\text{sum of micromoles of } C_6\text{-}C_{16} \text{ olefins}]$.

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Table 1b

Example	Ligand (0.3 μmol)	Chromium Precursor (0.3 μmol)	Method	Solvent	Reactor Temp (°C)	Activation method and mol equivalents	μmol catalyst	μmol 1-hexene produced	1-hexene Selectivity	μmol 1-octene produced	1-octene Selectivity	{1-hexene + 1-octene} selectivity	mg polyethylene produced
56	D3	$[(TFA)_2Cr(OEt_2)]_2$	1	Toluene	50	100 MMAO-3A/25 TIBA	0.3	25	29	56	64	93	5
57	C5	$(THF)_3CrMeCl_2$	2	Toluene	50	100 PMAO-IP/25 TMA	0.3	32	45	35	48	93	3
58	B2	$(THF)_3CrMeCl_2$	9	Heptane	50	200 MMAO-3A	0.3	36	43	47	57	>99	3
59	B2	$(THF)_3CrMeCl_2$	4	Heptane	50	200 MMAO-3A	0.3	34	74	12	26	>99	9
60	B2	$(THF)_3CrMeCl_2$	1	Toluene	50	200 MMAO-3A	0.3	23	37	32	50	87	6
61	D4	$(THF)_3CrMeCl_2$	1	Toluene	50	200 MMAO-3A	0.3	76	27	192	68	94	7
62	D4	$(THF)_3CrMeCl_2$	1	Toluene	50	100 MMAO-3A/25 TEAL	0.3	24	30	51	64	94	3
64	D4	$(THF)_3CrMeCl_2$	9	Heptane	50	200 MMAO-3A	0.3	23	28	54	66	94	4
64	D4	$(THF)_3CrMeCl_2$	4	Heptane	50	200 MMAO-3A	0.3	21	40	28	54	95	3
65	D4	$(THF)_3CrMeCl_2$	2	Toluene	50	200 MMAO-3A	0.3	19	37	29	56	93	4
66	D3	$[(TFA)_2Cr(OEt_2)]_2$	2	Toluene	50	100 MMAO-3A/25 TIBA	0.3	25	29	56	64	93	5
67	D3	$(THF)_3CrMeCl_2$	1	Toluene	50	100 MMAO-3A/25 TIBA	0.3	15	52	14	47	99	17
68	C5	$(THF)_3CrMeCl_2$	1	Toluene	50	100 PMAO-IP/25 TMA	0.3	32	45	35	49	93	3
69	C5	$[(TFA)_2Cr(OEt_2)]_2$	1	Toluene	50	100 MMAO-3A/25 TIBA	0.3	22	45	20	41	87	3
70	C5	$(THF)_3CrMeCl_2$	1	Toluene	50	100 MMAO-3A/25 TIBA	0.3	20	56	16	44	>99	2

Example 6: Selective Ethylene Oligomerization Reactions in a 48-Well Parallel Pressure Reactor**6a. Reactor Preparation**

- 5 **[0231]** A pre-weighed glass vial insert and disposable stirring paddle were fitted to each reaction vessel of the reactor.
- [0232] Method A.** The reactor was then closed, 0.330 mL of a 1.82 M solution of Modified Methylalumoxane 3A (from Akzo Chemical Inc., Chicago, IL) ("MMAO") in heptane and 4.70 mL of n-dodecane were injected into each pressure reaction vessel through a valve. The temperature was then set to the appropriate setting (with specific temperatures for each trimerization being listed in Table 2, below), and the stirring speed was set to 800 rpm, and the mixture was exposed to ethylene at 100 psi (0.67MPa) pressure. An ethylene pressure of 100 psi (0.67MPa) in the pressure cell and the temperature setting were maintained, using computer control, until the end of the selective oligomerization experiment.
- 10 **[0233] Method B.** The reactor was then closed, 0.256 mL of a 2.35 M solution of Modified Methylalumoxane 3A (from Akzo Chemical Inc., Chicago, IL) ("MMAO") in toluene and 4.75 mL of toluene were injected into each pressure reaction vessel through a valve. The temperature was then set to the appropriate setting (with specific temperatures for each trimerization being listed in Table 2, below), and the stirring speed was set to 800 rpm, and the mixture was exposed to ethylene at 100 psi (0.67MPa) pressure. An ethylene pressure of 100 psi (0.67MPa) in the pressure cell and the temperature setting were maintained, using computer control, until the end of the selective oligomerization experiment.
- 15 **[0234] Method C.** The reactor was then closed, 0.330 mL of a 1.82 M solution of Modified Methylalumoxane 3A (from Akzo Chemical Inc., Chicago, IL) ("MMAO") in heptane and 4.80 mL of heptane were injected into each pressure reaction vessel through a valve. The temperature was then set to the appropriate setting (with specific temperatures for each trimerization being listed in Table 2, below), and the stirring speed was set to 800 rpm, and the mixture was exposed to ethylene at 100 psi (0.67MPa) pressure. An ethylene pressure of 100 psi (0.67MPa) in the pressure cell and the temperature setting were maintained, using computer control, until the end of the selective oligomerization experiment.
- 20 **[0235] Method D.** Method D was similar to Method A, except that 0.330 mL of a 1.82 M solution of Modified Methylalumoxane 3A (from Akzo Chemical Inc., Chicago, IL) ("MMAO") in heptane and 4.80 mL of n-dodecane were injected into each pressure reaction vessel through a valve. The temperature and ethylene pressure were then set and maintained as in Method A.
- 25

6b. In-Situ Preparation of Chromium-Ligand Compositions

- 30 **[0236]** The following methods were employed to prepare chromium-ligand compositions for the examples presented in Table 2.
- [0237] Method AA.** 44 μ l of the ligand solution (25 mM in toluene) was dispensed in a 1 mL glass vial in which a magnetic stir bar had been placed. To the 1 mL glass vial containing the ligand solution was added 110 μ L of CrMeCl₂ (THF)₃ solution (10 mM in toluene) to form the metal-ligand composition. The reaction mixture was heated to 75°C for 30 minutes, with stirring. The solvent was then removed by passing a stream of argon over the reaction mixture. 150 μ L of n-dodecane was then added to the metal-ligand composition, and the resulting mixture was stirred throughout subsequent activator addition and sampling steps.
- 35 **[0238] Method BB.** Method BB was similar to method AA except that toluene solvent was not removed and n-dodecane was not added.
- 40 **[0239] Method CC.** 40 μ l of the ligand solution (25 mM in toluene) was dispensed in a 1 mL glass vial in which a magnetic stir bar had been placed. To the 1 mL glass vial containing the ligand solution was added 100 μ L of CrMeCl₂ (THF)₃ solution (10 mM in toluene) to form the metal-ligand composition. The reaction mixture was heated to 75°C for 30 minutes with stirring. The solvent was then removed by passing a stream of argon over the reaction mixture. 130 μ L of heptane was then added to the metal-ligand composition, and the resulting mixture was stirred throughout subsequent activator addition and sampling steps.
- 45 **[0240] Method DD.** 50 μ l of the ligand solution (20 mM in THF) was dispensed in a 1 mL glass vial in which a magnetic stir bar had been placed. To the 1 mL glass vial containing the ligand solution was added 100 μ L of [(TFA)₂Cr(OEt₂)₂]₂ solution (10 mM (Cr concentration) in THF) to form the metal-ligand composition. The reaction mixture was stirred at room temperature for 2.5 hours. The solvent was then removed by passing a stream of argon over the reaction mixture. 150 μ L of n-dodecane was then added to the metal-ligand composition, and the resulting mixture was stirred throughout subsequent activator addition and sampling steps.
- 50 **[0241] Method EE.** 100 μ l of the ligand solution (10 mM in n-dodecane) was dispensed in a 1 mL glass vial in which a magnetic stir bar had been placed. To the 1 mL glass vial containing the ligand solution was added 200 μ L of a 5 mM stirred suspension of (Mes)CrCl(THF)₂ in n-dodecane, to form the metal-ligand composition. The reaction mixture was stirred at room temperature for 3 hours, and the resulting mixture was stirred throughout subsequent activator addition and sampling steps.
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6c. Preparation of the Group 13 Reagent and Activator Stock Solutions

[0242] The 600 mM solution of Modified Methylalumoxane 3A ("MMAO") in toluene was prepared by combining 5.10 mL of a 2.35 M solution of MMAO-3A in toluene (purchased from Akzo Chemical Inc., Chicago, IL) and 14.89 mL of toluene. The 600 mM solution of MMAO in heptane/n-dodecane was prepared by combining 6.60 mL of a 1.82 M solution of MMAO-3A in heptane (purchased from Akzo Chemical Inc., Chicago, IL) and 13.40 mL n-dodecane. The 600 mM solution of MMAO in heptane was prepared by combining 6.60 mL of a 1.82 M solution of MMAO-3A in heptane (purchased from Akzo Chemical Inc., Chicago, IL) and 13.40 mL heptane. The 200 mM solution of TIBA (Triisobutylaluminum) in n-dodecane was prepared by combining 1.59g of neat Triisobutylaluminum (purchased from Aldrich, Milwaukee, WI) and 37.98 mL of n-dodecane. The 5 mM solution of "SJ2BF20" (N,N-di(n-decyl)-4-n-butyl-anilinium tetrakis(perfluorophenyl) borate, $[(4-n\text{-Bu-C}_6\text{H}_4)\text{NH}(n\text{-decyl})_2]^+[\text{B}(\text{C}_6\text{F}_5)_4]^-$) in n-dodecane was prepared by combining 0.111g of "SJ2BF20" (N,N-di(n-decyl)-4-n-butyl-anilinium tetrakis(perfluorophenyl)borate, $[(4-n\text{-Bu-C}_6\text{H}_4)\text{NH}(n\text{-decyl})_2]^+[\text{B}(\text{C}_6\text{F}_5)_4]^-$) and 20 mL of n-dodecane, and was heated to approximately 85°C, with stirring, prior to and during use.

6d. Activation Methods and Injection of Solutions into the Pressure Reactor Vessel

[0243] The following methods were employed to activate and inject the in-situ prepared chromium-ligand compositions into the parallel pressure reactor. The examples are presented in Table 2.

[0244] **Method AAA.** To the stirred metal-ligand composition in n-dodecane, 367 μL of a 600mM solution of MMAO-3A in heptane/n-dodecane was added. After approximately 8 minutes, 50 μL n-dodecane were added to the 1 mL vial and the reaction mixture was mixed. Approximately 30 seconds later, a fraction of the 1 mL vial contents corresponding to 0.80 micromoles (μmol) of chromium precursor (412 μL), was injected into the prepressurized reaction vessel and was followed immediately by injection of n-dodecane to bring the total volume injected to 1.0 mL.

[0245] **Method BBB.** To the stirred metal-ligand composition in toluene, 367 μL of a 600mM solution of MMAO-3A in toluene was added. After approximately 8 minutes, 50 μL toluene were added to the 1 mL vial and the reaction mixture was mixed. Approximately 30 seconds later, a fraction of the 1 mL vial contents corresponding to 0.80 micromoles (μmol) of chromium precursor (412 μL), was injected into the prepressurized reaction vessel and was followed immediately by injection of toluene to bring the total volume injected to 1.0 mL.

[0246] **Method CCC.** To the stirred metal-ligand composition in toluene, 333 μL of a 600mM solution of MMAO-3A in heptane was added. After approximately 8 minutes, 50 μL heptane were added to the 1 mL vial and the reaction mixture was mixed. About another 30 seconds later, a fraction of the 1 mL vial contents corresponding to 0.60 micromoles (μmol) of metal precursor (308 μL), was injected into the prepressurized reaction vessel and was followed immediately by injection of n-dodecane to bring the total volume injected to 1.0 mL.

[0247] **Method DDD.** To the stirred metal-ligand composition in n-dodecane, 333 μL of a 600mM solution of MMAO-3A in heptane/n-dodecane was added. After approximately 12 minutes, 150 μL n-dodecane were added to the 1 mL vial and the reaction mixture was mixed. Approximately 60 seconds later, a fraction of the 1 mL vial contents corresponding to 0.60 micromoles (μmol) of chromium precursor (380 μL), was injected into the prepressurized reaction vessel and was followed immediately by injection of n-dodecane to bring the total volume injected to 1.0 mL.

[0248] **Method EEE.** To the stirred metal-ligand composition in n-dodecane, 240 μL of a 5mM solution of "SJ2BF20" (N,N-di(n-decyl)-4-n-butyl-anilinium tetrakis(perfluorophenyl)borate, $[(4-n\text{-Bu-C}_6\text{H}_4)\text{NH}(n\text{-decyl})_2]^+[\text{B}(\text{C}_6\text{F}_5)_4]^-$) in n-dodecane was added. After approximately 12 minutes, 150 μL of a 200mM solution of TIBA (Triisobutylaluminum) in n-dodecane was added to the 1 mL vial and the reaction mixture was mixed. Approximately 60 seconds later, a fraction of the 1 mL vial contents corresponding to 0.60 micromoles (μmol) of chromium precursor (324 μL), was injected into the prepressurized reaction vessel and was followed immediately by injection of n-dodecane to bring the total volume injected to 1.0 mL.

[0249] **Method FFF.** To the stirred metal-ligand composition in n-dodecane, 150 μL of a 200mM solution of TIBA (Triisobutylaluminum) in n-dodecane was added. After approximately 12 minutes, 150 μL of n-dodecane was added to the 1 mL vial and the reaction mixture was mixed. Approximately 60 seconds later, a fraction of the 1 mL vial contents corresponding to 0.60 micromoles (μmol) of chromium precursor (360 μL), was injected into the prepressurized reaction vessel and was followed immediately by injection of n-dodecane to bring the total volume injected to 1.0 mL.

6e. Oligomerization Reactions

[0250] The trimerization reactions were allowed to continue for between 4.6 minutes and 60 minutes, during which time the temperature and pressure were maintained at their pre-set levels by computer control. The specific reaction times for each experiment are shown in Table 2. After the reaction time elapsed, the reaction was quenched by addition of an overpressure of oxygen (approximately 35 psi (241 kPa) of a 20% O_2 / 80% N_2 mixture) sent to the reactor. The reaction times were the lesser of the maximum desired reaction time or the time taken for a predetermined amount of

ethylene gas to be consumed in the reaction.

6f. Product Analysis

- 5 **[0251]** After completion of the trimerizations reactions, the glass vial inserts containing the reaction products were removed from the pressure cell and removed from the inert atmosphere dry box, and deionized water (50 mL -100 mL) was added. The glass vial inserts were then centrifuged for approximately 10 minutes. 0.5 mL of the supernatant was then removed and analyzed by the GC-FID technique. The remaining supernatant was then decanted, and the vial insert containing insoluble residue was then placed in a centrifuge evaporator and the volatile components were removed.
- 10 After most of the volatile components had evaporated, the vial contents were dried thoroughly (to constant weight) by evaporation at elevated temperature (approximately 80°C) under reduced pressure in a vacuum oven. The vial was then weighed to determine the mass of solid product (final weight minus vial tare weight). The calculated mass of the catalyst and cocatalyst residue was then subtracted from the total mass to give the yield of polyethylene produced. *Table 2* presents the results from the ethylene oligomerization reactions performed in a 48-well parallel pressure reactor.
- 15 **[0252]** In Table 2, 1-hexene selectivity is shown as a percentage and is defined as $100 \times [\text{micromoles of 1-hexene}] / [\text{sum of micromoles of } C_6\text{-}C_{16} \text{ olefins (excluding dodecene when dodecane is used as solvent)}]$.
- [0253]** Catalyst activity (TOF) for production of the desired oligomer (1-hexene) is defined as the $[\text{micromoles of 1-hexene}] / [\text{micromoles of catalyst}] / [\text{reaction time in minutes}] * 60 \text{ minutes/hour}$, as shown in the column "1-hexene TOF".

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Table 2:

	mg polyethylene produced	25	17	<2
	1-hexane TOF (mole/mole.hour)	1270	2130	480
	1-hexene selectivity	96	98	87
	micromole 1-hexene produced	570	760	220
	Reaction Time (min)	45	35.8	45
	micromole catalyst	0.6	0.6	0.6
	Group 13 reagent amount in reactor (micromole)	600 MMAO-3A	600 MMAO-3A	600 MMAO-3A
	Activation method and mol equivalents versus Cr	200 MMAO-3A	1.2 SJ2BF20/30 TIBA	30 TIBA
	Reactor Temp (°C)	80	80	80
	Solvent	Dodecane	Dodecane	Dodecane
	Activation Method	DDD	EEE	FFF
	Complexation Method	DD	DD	EE
	Reactor Preparation Method	D	D	D
	Chromium Precursor	$[(TFA)_2Cr(OEt_2)]_2$	$[(TFA)_2Cr(OEt_2)]_2$	$Cr(Mes)Cl(THF)_2$
	Ligand	C1	C1	C1
	Example	73	74	75

6g. Synthesis of Isolated Chromium-Ligand Compositions Comment on Complex Nomenclature**Synthesis of M1**

5 **[0254]** Solid $\text{CrMeCl}_2(\text{THF})_3$ (33.9 mg, 0.0957 mmol, 1 equiv) was added to a toluene solution of ligand C5 (36.2 mg, 0.0956 mmol, 1 equiv, 3 mL toluene) at room temperature. The reaction mixture was stirred at 75 °C for 90 minutes, during which time the reaction mixture turned from a bright green solution to an olive green-brown solution. The reaction mixture was cooled to room temperature, and the toluene was removed under a nitrogen stream to leave an olive-green solid residue. The solid was dried under vacuum for 2 hours. The solid was dissolved in CH_2Cl_2 (5 mL), and a THF slurry of Li(acac) (10 mg, 0.0942 mmol, 1 equiv, 2 mL THF) was added at room temperature (where acac = acetylacetonate = 2,4-pentanedionate). The resulting mixture was stirred and heated to 75 °C for 60 minutes, during which time the mixture turned orange-brown. The mixture was cooled to RT, and the solvent was removed under a stream of nitrogen. The product was taken up in toluene to form a purple solution and filtered to remove white solids. The filter was washed with 2 x 1 mL of toluene, and the combined filtrate was dried under a stream of nitrogen to leave a purple-brown residue. 15 The solid was dried *in vacuo* for 2 hours. 57 mg of product was obtained.

Ligand #	Complex #	Amount $\text{CrMeCl}_2(\text{THF})_3$	Amount of Ligand	Amount Li(acac)	Yield	Color
D4	M2	38 mg	35 mg	11 mg	51 mg	orange-brown

Example 7: Selective Ethylene Oligomerization Reactions in a 48-Well Parallel Pressure Reactor

25 **[0255]** Ethylene oligomerization experiments described below were carried out in a parallel pressure reactor described in U.S. Patents 6,759,014 and 6,913,934. All air-sensitive procedures were performed under a purified argon or nitrogen atmosphere in a Vacuum Atmospheres or MBraun glove box. All solvents used were anhydrous and de-oxygenated. All glassware and the disposable paddles were dried in a vacuum oven at 200°C for at least 24 hours.

7a. Stock Solution & Suspension Preparation**Preparation of the Group 13 Reagent and Activator Stock Solutions**

35 **[0256]** A 200 mM solution of DIBAL (diisobutylaluminum hydride) in heptane was prepared by combining 1.14 g of neat diisobutylaluminum hydride (purchased from Aldrich, Milwaukee, WI) and 38.6 mL of heptane. The 50 mM solution of DIBAL in heptane was prepared by further dilution of the 200 mM solution of DIBAL in heptane.

[0257] A 400 mM solution of MMAO-3A in heptane was prepared by combining 8.80 mL of a 1.82 M solution of MMAO-3A in heptane (purchased from Akzo Chemical Inc., Chicago, IL) and 31.2 mL heptane.

Preparation of Complex Solutions

40 **[0258]** For Example 2.1, 4.8 mg of **Complex M1** was dissolved in 4.70 mL of toluene, in an 8mL glass vial, to give a 2.0 mM solution. For Examples 2.2, 4.7 mg of **Complex M2** was dissolved in 4.70 mL of toluene, in an 8mL glass vial, to give a 2.0 mM solution.

7b. Reactor Preparation for Examples 7.1 & 7.2

45 **[0259]** A pre-weighed, pre-dried, glass vial insert and disposable stirring paddle were fitted to each reaction vessel of the reactor.

50 **[0260]** The reactor was then closed, 0.200 mL of a 50 mM solution of DIBAL in heptane and 3.600 mL of heptane (to achieve a total liquid volume of 5.10 mL after the catalyst injection step), were injected into the pressure reaction vessel through a mechanical septum. The temperature was then set to 80°C, and the stirring speed was set to 800 rpm, and the mixture was exposed to ethylene at 400 psi (2.76 MPa) pressure. An ethylene pressure of 400 psi (2.76 MPa) in the pressure cell and the temperature setting were maintained, using computer control, until the end of the selective oligomerization experiment.

7c. Injection of Activator Solution and Catalyst Solution into the Pressure Reactor Vessel for Example 7.1 & 7.2:**Activator Injection Step:**

5 [0261] 0.300 mL of a 200 mM solution of MMAO-3A in heptane was robotically aspirated into a needle (as described in U.S. Patents 6,759,014 and 6,913,934), followed by the aspiration of 0.080 mL of heptane. The outside of the needle was sprayed with heptane, then the needle contents (heptane and MMAO-3A solution) were injected into the pressurized reaction vessel through a mechanical septum, followed immediately by injection of 0.320 mL of heptane.

Complex Injection Step:

10 [0262] 0.200 mL of a 2.0 mM solution of **Complex M1 (for Example 7.1) or complex M2 (for Example 7.2)** in toluene was robotically aspirated from an 8 ml glass vial, followed by the aspiration of 0.080 mL of heptane. The outside of the needle was sprayed with heptane, then the needle contents (heptane and complex solution) were injected into the pressurized reaction vessel through a mechanical septum, followed immediately by injection of 0.320 mL of heptane, to bring the total volume injected to 0.600 mL. The Complex injection into the pressurized reaction vessel occurred 2 minutes after the Activator injection.

7d. Oligomerization Reactions

20 [0263] The oligomerization reactions were allowed to continue for between 47 minutes and 60 minutes, during which time the temperature and pressure were maintained at their pre-set levels by computer control. The specific reaction times for each experiment are shown in **Table 3**. After the reaction time elapsed, the reaction was quenched by addition of an overpressure of oxygen (approximately 50 psi (0.34 MPa) of a 20% O₂ / 80% N₂ mixture) sent to the reactor. The reaction times were the lesser of the maximum desired reaction time or the time taken for a predetermined amount of ethylene gas to be consumed in the reaction.

7e. Product Analysis

30 [0264] After completion of the oligomerization reactions, the glass vial inserts containing the reaction products were removed from the pressure cell and removed from the inert atmosphere dry box, and deionized water (100 μL) was added. The glass vial inserts were then centrifuged for approximately 10 minutes. After centrifuging, 500 μL of the supernatant was then removed and analyzed by the GC-FID technique described above. The remaining supernatant was then decanted, and the vial insert containing insoluble residue was then placed in a centrifuge evaporator and the volatile components were removed. After the volatile components had evaporated, the vial contents were dried thoroughly (to constant weight) at elevated temperature (approximately 80°C) under reduced pressure in a vacuum oven. The vial was then weighed to determine the mass of solid product (final weight minus vial tare weight). The calculated mass of the catalyst and cocatalyst residue was then subtracted from the total mass to give the yield of polyethylene produced, as listed in **Table 3**.

35 [0265] **Table 3** presents the results from the ethylene oligomerization reactions performed in a 48-well parallel pressure reactor. In **Table 3**, 1-hexene selectivity is shown as a percentage and is defined as $100 \times [\text{micromoles of 1-hexene}] / [\text{sum of micromoles of C}_5\text{-C}_{16} \text{ olefins}]$. 1-octene selectivity is shown as a percentage and is defined as $100 \times [\text{micromoles of 1-octene}] / [\text{sum of micromoles of C}_6\text{-C}_{16} \text{ olefins}]$. Catalyst activity (Turn Over Frequency, TOF) for production of the desired oligomers (1-hexene + 1-octene) is defined as the $[\text{micromoles of (1-hexene + 1-octene)}] / ([\text{micromoles of catalyst}] * [\text{reaction time in minutes}] / 60)$, as shown in the column "(1-hexene + 1-octene) TOF". In **Table 3**, MMAO-3A is abbreviated to "MMAO".

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Table 3

Example #	Ligand #	Complex #	micromoles of Complex	micromoles of Group 13 Reagent	Molar Equiv. of Activator (vs. Complex)	Reaction Time (mins)	micromoles of 1-hexene	micromoles of 1-octene	1-Hexene Selectivity (%)	1-Octene Selectivity (%)	(1-Hexene + 1-Octene) Selectivity (%)	(1-Hexene + 1-Octene) TOF (per hr)	Poly ethylene (mg)
7.1	C5	M1	0.4	10 DIBAL	300 MMAO	47.3	587	327	63.5	35.4	98.8	2895	18
7.2	D4	M2	0.4	10 DIBAL	300 MMAO	60.0	672	574	53.4	45.7	99.1	3114	9

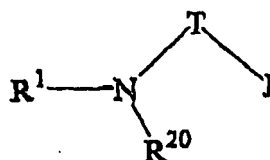
[0266] As discussed herein, catalytic performance can be determined a number of different ways, as those of skill in the art will appreciate. Catalytic performance can be determined by the yield of oligomer (for example, trimer or tetramer) obtained per mole of metal complex, which in some contexts may be considered to be activity.

[0267] The results of selective ethylene trimerization or tetramerization using ligands of the invention in combination with chromium precursors or with isolated chromium metal complexes are surprising. The results illustrate that certain combinations are more productive in the trimerization of ethylene, for example, to produce 1-hexene at a higher selectivity and a lower selectivity toward polyethylene when compared with other chromium-ligand catalysts under similar conditions.

Claims

1. A method of producing oligomers of olefins, comprising reacting an olefin with a catalyst, wherein said oligomerization reaction has a selectivity of at least 70 mole percent for oligomer, and wherein said catalyst is formed from the combination of:

(1) a ligand **characterized by** the following general formula:



wherein R^1 and R^{20} are each independently selected from the group consisting of hydrogen and optionally substituted hydrocarbyl, heteroatom containing hydrocarbyl and silyl, provided that R^1 or R^{20} do not equal T-J, where T-J is as given by the general formula above and defined below;

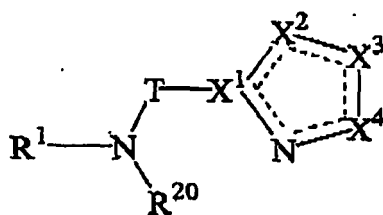
T is a bridging group of the general formula $-(T'R^2R^3)-$, where T' is selected from the group consisting of carbon and silicon, R^2 and R^3 are independently selected from the group consisting of hydrogen, halogen, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, provided that two or more R^2 and/or R^3 groups may be joined together to form one or more optionally substituted ring systems having from 3-50 non-hydrogen atoms;

J is an optionally substituted five-membered heterocycle, containing at least one nitrogen atom as part of the ring, with the further proviso that J contains at least two, but not more than four, heteroatoms;

(2) a metal precursor compound **characterized by** the general formula $Cr(L)_n$ where each L is independently selected from the group consisting of halide, alkyl, substituted alkyl, cycloalkyl, substituted cycloalkyl, heteroalkyl, substituted heteroalkyl, heterocycloalkyl, substituted heterocycloalkyl, aryl, substituted aryl, heteroaryl, substituted heteroaryl, alkoxy, aryloxy, hydroxy, boryl, silyl, amino, amine, hydrido, allyl, diene, seleno, phosphino, phosphine, ether, thioether, carboxylates, thio, 1,3-dionates, oxalates, carbonates, nitrates, sulfates, ethers, thioethers and combinations thereof, wherein two or more L groups may be combined in a ring structure having

from 3 to 50 non-hydrogen atoms; n is 1, 2, 3, 4, 5, or 6; and
(3) optionally, one or more activators.

2. The method of claim 1, wherein the ligand is characterized by the following general formula:

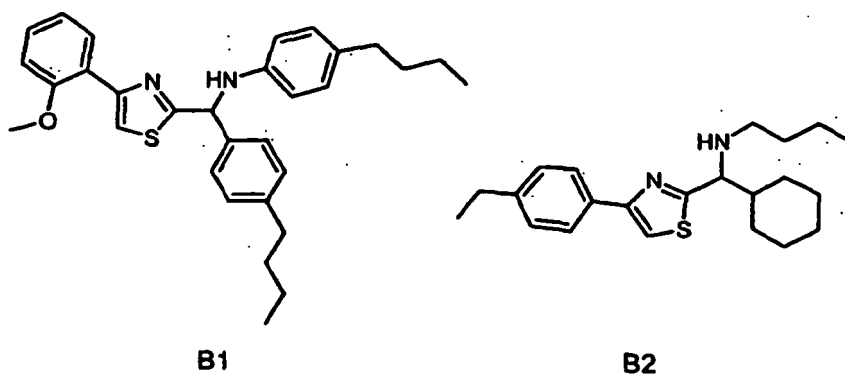


wherein R^1 , R^{20} , and T are described above; and X^1 is nitrogen or $-C(R^8)_{n'}$, X^2 , X^3 , and X^4 are selected from the group consisting of oxygen, sulfur, $-C(R^8)_{n'}$, $-N(R^8)_{n'}$, and provided that X^1 is $-C(R^8)_{n'}$ or at least one of X^2 , X^3 , or X^4 is $-C(R^8)_{n'}$.

each n' is 1 or 2 and each n'' is 0 or 1; and,

each R^8 is independently selected from the group consisting of hydrogen, halogen, nitro, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, and optionally two or more R^1 , R^{20} , R^2 , R^3 , and R^8 groups may be joined to form one or more optionally substituted ring systems.

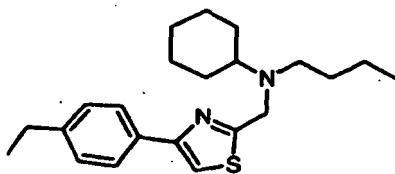
3. The method of 1, wherein R^1 and R^{20} are each independently selected from hydrogen and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, silyl and combinations thereof.
4. The method of claim 2, wherein R^1 and R^{20} are each independently selected from hydrogen and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, silyl and combinations thereof.
5. The method of claim 2, wherein R^1 is hydrogen and R^{20} is selected from optionally substituted alkyl, heteroalkyl, cycloalkyl, heterocycloalkyl, silyl and combinations thereof.
6. The method of claim 1, wherein the ligand comprises:



B1

B2

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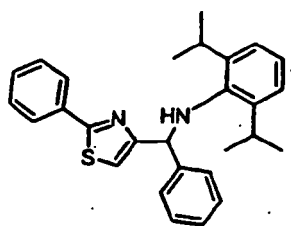


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B3

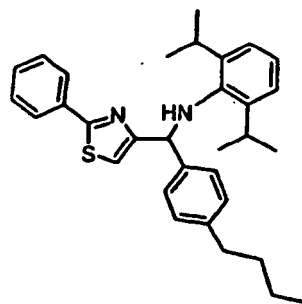
7. The method of claim 1, wherein the ligand is selected from the group consisting of:

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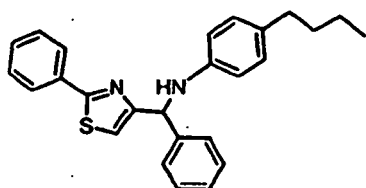
C1

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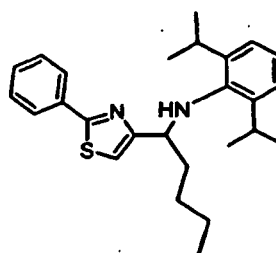
C2

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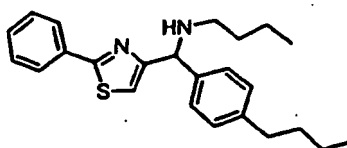
C3

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C4

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C5

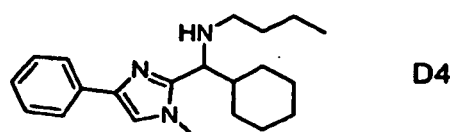
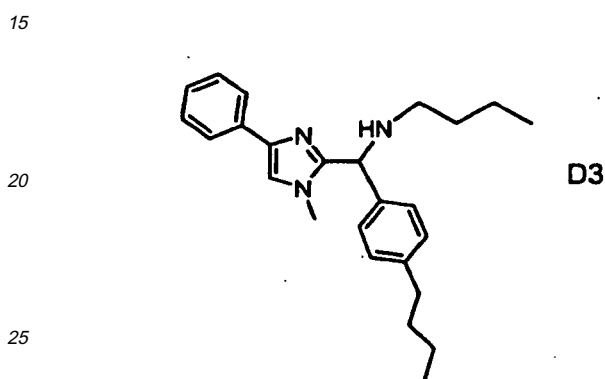
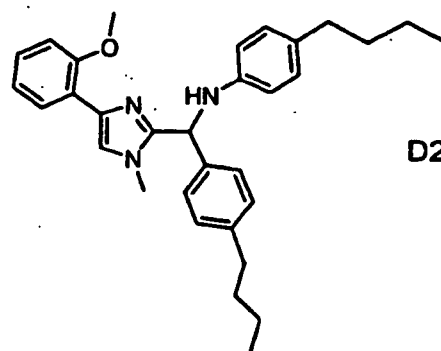
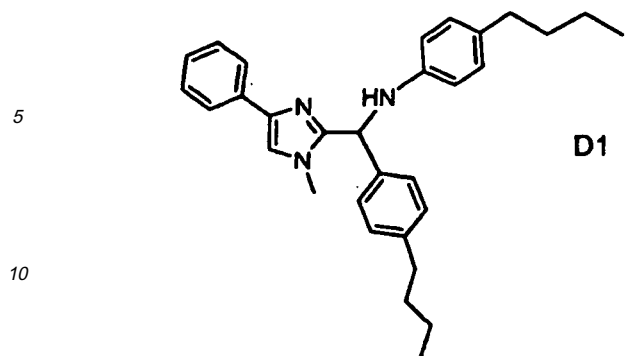
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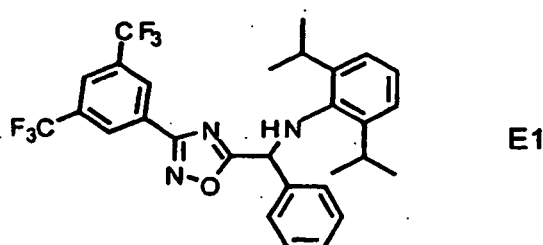
8. The method of claim 1, wherein the ligand is selected from the group consisting of:

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30 9. The method of claim 1, wherein the ligand comprises



45 10. The method of any one of claims 1 through 9, wherein the activator is an alumoxane, which may optionally be used in any combination with group 13 reagents, divalent metal reagents, or alkali metal reagents.

50 11. The method of any one of claims 1 through 9, wherein the activator is a neutral or ionic stoichiometric activator, which may optionally be used in any combination with group 13 reagents, divalent metal reagents, or alkali metal reagents.

55 12. The method of any one of claims 1 through 9, wherein the activator is selected from the group consisting of modified methylalumoxane (MMAO), methylalumoxane (MAO), trimethylaluminum (TMA), triisobutyl aluminum (TIBA), diisobutylaluminumhydride (DIBAL), polymethylalumoxane-IP (PMAO), triphenylcarbonium tetrakis(perfluorophenyl) borate, N,N-dimethylanilinium tetrakis(perfluorophenyl)borate, N,N-di(n-decyl)-4-n-butylanilinium tetrakis(perfluorophenyl)borate, and mixtures thereof.

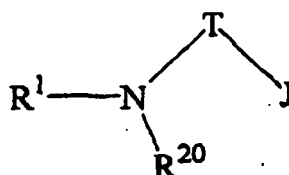
13. The method of any one of claims 1 through 9, wherein the metal precursor is selected from the group consisting of $(\text{THF})_3\text{CrMeCl}_2$, $(\text{THF})_3\text{CrCl}_3$, $(\text{Mes})_3\text{Cr}(\text{THF})$, $[\{\text{TFA}\}_2\text{Cr}(\text{OEt}_2)]_2$, $(\text{THF})_3\text{Cr}(\eta^2\text{-2,2-biphenyl})\text{Br}$, $(\text{THF})_3\text{CrPh}_3$ and mixtures thereof.

14. The method of claim 1, wherein the olefin is a C_2 to C_{12} olefin.

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15. The method of claim 1, wherein the olefin is a C₂ to C₈ olefin.
16. The method of claim 1, wherein the olefin is ethylene.
- 5 17. The method of claim 16, wherein the process produces a trimer or a tetramer of the olefin.
18. The method of claim 17, wherein the process produces 1-hexene.
19. The method of claim 17, wherein the process produces 1-octene.
- 10 20. The method of claim 16 wherein the process produces a mixture of 1-hexene and 1-octene.
21. The method of claim 1 wherein the reaction occurs in a hydrocarbon solvent.
- 15 22. The method of claim 21 wherein the reaction occurs in an aliphatic hydrocarbon solvent.
23. A composition comprising:

(1) a ligand **characterized by** the following general formula:



30 wherein R¹ and R²⁰ are each independently selected from the group consisting of hydrogen and optionally substituted alkyl, provided that R¹ or R²⁰ do not equal T-J, where T-J is as given by the general formula above and defined below;

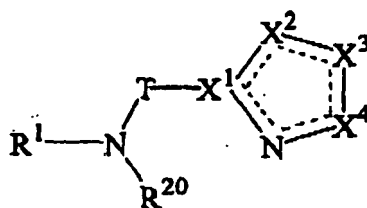
T is a bridging group of the general formula -(T'R²R³)-, where T' is selected from the group consisting of carbon and silicon, R² and R³ are independently selected from the group consisting of hydrogen, halogen, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, provided that two or more R² and/or R³ groups may be joined together to form one or more optionally substituted ring systems having from 3-50 non-hydrogen atoms;

J is an optionally substituted five-membered heterocycle, containing at least one nitrogen atom as part of the ring with the further proviso that J contains at least two, but not more than four, heteroatoms;

(2) a metal precursor compound **characterized by** the general formula Cr(L)_n where each L is independently selected from the group consisting of halide, alkyl, substituted alkyl, cycloalkyl, substituted cycloalkyl, heteroalkyl, substituted heteroalkyl heterocycloalkyl, substituted heterocycloalkyl, aryl, substituted aryl, heteroaryl, substituted heteroaryl, alkoxy, aryloxy, hydroxy, boryl, silyl, amino, amine, hydrido, allyl, diene, seleno, phosphino, phosphine, ether, thioether, carboxylates, thio, 1,3-dionates, oxalates, carbonates, nitrates, sulfates, ethers, thioethers and combinations thereof, wherein two or more L groups may be combined in a ring structure having from 3 to 50 non-hydrogen atoms; n is 1, 2, 3, 4, 5, or 6; and

(3) optionally, one or more activators.

24. The composition of claim 23, wherein the ligand is **characterized by** the following general formula:

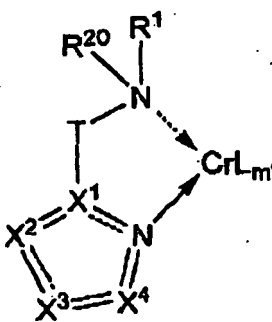


wherein R^1 , R^{20} , and T are described above; and X^1 is nitrogen or $-C(R^8)_n-$, X^2 , X^3 , and X^4 are selected from the group consisting of oxygen, sulfur, $-C(R^8)_n-$, $-N(R^8)_n-$, and provided that X^1 is $-C(R^8)_n-$ or at least one of X^2 , X^3 , or X^4 is $-C(R^8)_n-$

each n' is 1 or 2 and each n'' is 0 or 1; and,

each R^8 is independently selected from the group consisting of hydrogen, halogen, nitro, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, and optionally two or more R^1 , R^{20} , R^2 , R^3 , and R^8 groups may be joined to form one or more optionally substituted ring systems.

25. A metal complex characterized by the following general formula:



wherein R^1 and R^{20} are each independently selected from the group consisting of hydrogen and optionally substituted alkyl, heteroalkyl, cycloalkyl, heterocycloalkyl, aryl, heteroaryl, silyl and combinations thereof;

X^1 is nitrogen or $-C(R^8)_n-$, X^2 , X^3 and X^4 are independently selected from the group consisting of oxygen, sulfur, $-C(R^8)_n-$ or $-N(R^8)_n-$, where each n' is 1 or 2, and each n'' is 0 or 1, and each R^8 is independently selected from the group consisting of hydrogen, halogen, nitro, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof with the proviso that at least one, but no more than three, of X^1 , X^2 , X^3 and X^4 is a heteroatom;

T is a bridging group of the general formula $-(T'R^2R^3)-$, where T' is selected from the group consisting of carbon and silicon, R^2 and R^3 are independently selected from the group consisting of hydrogen, halogen, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, provided that two or more R^2 and/or R^3 groups may be joined together to form one or more optionally substituted ring systems having from 3-50 non-hydrogen atoms; any combination of two or more R^1 , R^2 , R^3 , and/or R^8 groups may be joined together to form one or more optionally substituted fused ring systems;

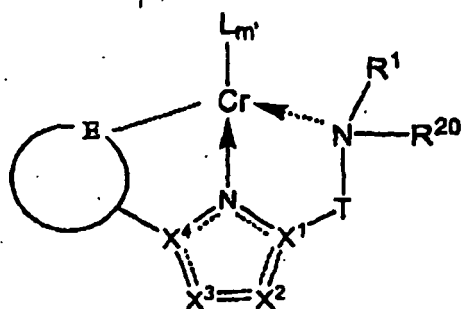
each L is independently selected from the group consisting of halide, alkyl, substituted alkyl, cycloalkyl, substituted cycloalkyl, heteroalkyl, substituted heteroalkyl heterocycloalkyl, substituted heterocycloalkyl, aryl, substituted aryl, heteroaryl, substituted heteroaryl, alkoxy, aryloxy, hydroxy, boryl, silyl, amino, amine, hydrido, allyl, diene, seleno, phosphino, phosphine, ether, thioether, carboxylates, thio, 1,3-dionates, oxalates, carbonates, nitrates, sulfates, ethers, thioethers and combinations thereof, wherein two or more L groups may be combined in a ring structure having from 3 to 50 non-hydrogen atoms;

m' is 1, 2 or 3; and

a dashed arrow indicates that the dative bond is an optional bond which may or may not be present.

26. The complex of claim 25, wherein R^8 is optionally substituted aryl or heteroaryl, and R^8 and M are optionally joined to form a metallocycle.

27. A metal complex characterized by the following general formula:



wherein R^1 and R^{20} are each independently selected from the group consisting of hydrogen and optionally substituted alkyl, heteroalkyl, cycloalkyl, heterocycloalkyl, aryl, heteroaryl, silyl and combinations thereof;

15 X^1 is nitrogen or $-C(R^8)_n-$, X^2 , X^3 and X^4 are independently selected from the group consisting of oxygen, sulfur, $-C(R^8)_n-$ or $N(R^8)_n-$, where each n' is 1 or 2, and each n'' is 0 or 1, and each R^8 is independently selected from the group consisting of hydrogen, halogen, nitro, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, with the proviso that at least one, but no more than three, of X^1 , X^2 , X^3 and X^4 is a heteroatom;

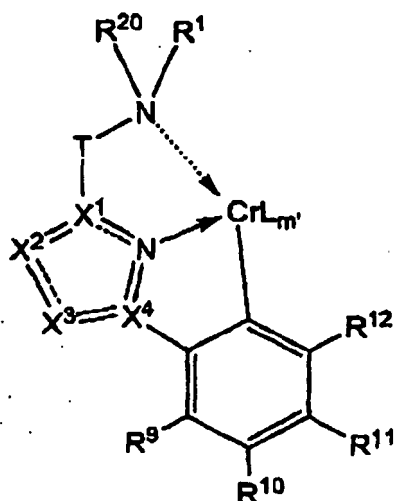
20 T is a bridging group of the general formula $-(T'R^2R^3)-$, where T' is selected from the group consisting of carbon and silicon, R^2 and R^3 are independently selected from the group consisting of hydrogen, halogen, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, provided that two or more R^2 and/or R^3 groups may be joined together to form one or more optionally substituted ring systems having from 3-50 non-hydrogen atoms; any combination of two or more R^1 , R^2 , R^3 , and/or R^8 groups may be joined together to form one or more optionally substituted fused ring systems.

25 each L is independently selected from the group consisting of halide, alkyl, substituted alkyl, cycloalkyl, substituted cycloalkyl, heteroalkyl, substituted heteroalkyl, heterocycloalkyl, substituted heterocycloalkyl, aryl, substituted aryl, heteroaryl, substituted heteroaryl, alkoxy, aryloxy, hydroxy, boryl, silyl, amino, amine, hydrido, allyl, diene, seleno, phosphino, phosphine, ether, thioether, carboxylates, thio, 1,3-dionates, oxalates, carbonates, nitrates, sulfates, ethers, thioethers and combinations thereof, wherein two or more L groups may be combined in a ring structure having from 3 to 50 non-hydrogen atoms; m' is 1, 2 or 3;

30 E is a carbon atom that is part of an optionally substituted aryl or heteroaryl ring; and

a dashed arrow indicates that the dative bond is an optional bond which may or may not be present.

35 **28.** The complex of claim 27, wherein the complex is characterized by the formula:

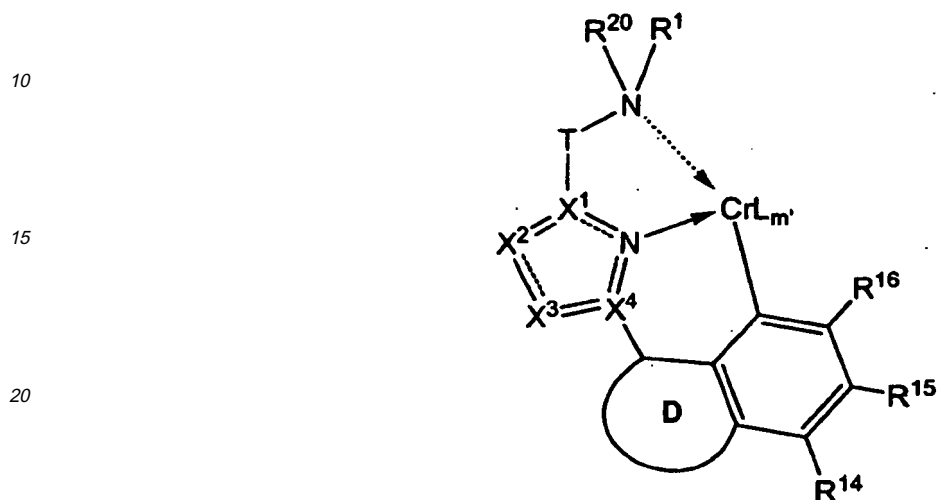


55 wherein R^1 , R^{20} , X^1 , X^2 , X^3 , X^4 , L, T and m' are as defined above;

R^9 , R^{10} , R^{11} , and R^{12} are each independently selected from the group consisting of hydrogen, halogen, nitro, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio,

arylthio, and combinations thereof, provided that optionally, two or more of R⁹, R¹⁰, R¹¹ and R¹² may be joined to form one or more optionally substituted fused ring systems; and
 a dashed arrow indicates that the dative bond is an optional bond which may or may not be present.

5 29. The complex of claim 27, wherein the complex is characterized by the formula:



25 wherein R¹, R²⁰, X¹, X², X³, X⁴, L, T and m' are as defined above;
 R¹⁴, R¹⁵ and R¹⁶ are each independently selected from the group consisting of hydrogen, halogen, nitro, and optionally substituted alkyl, heteroalkyl, aryl, heteroaryl, alkoxy, aryloxy, silyl, boryl, phosphino, amino, alkylthio, arylthio, and combinations thereof, provided that optionally, two
 30 or more of R¹⁴, R¹⁵ and R¹⁶ may be joined to form one or more optionally substituted fused ring systems;
 D is a ring selected from the group consisting of optionally substituted aryl and heteroaryl; and
 a dashed arrow indicates that the dative bond is an optional bond which may or may not be present.

35 30. A method of producing oligomers of olefins, comprising reacting an olefin with a catalyst under oligomerization conditions, wherein said oligomerization reaction has a selectivity of at least 70 mole percent for oligomer, and wherein said catalyst is selected from one of claims 25 through 29, and optionally, an activator.

31. The method of claim 30, wherein the olefin is ethylene.

40 32. The method of claim 31, wherein the process produces a trimer or a tetramer of the olefin.

33. The method of claim 32, wherein the process produces 1-hexene.

45 34. The method of claim 32, wherein the process produces 1-octene.

50 35. A method of producing oligomers of olefins, comprising reacting an olefin with a catalyst, wherein said oligomerization reaction produces two oligomers wherein the combined selectivity of the two oligomers sums to at least 70 mole percent, and wherein said catalyst is comprised of the metal complexes selected from one of claims 23 through 29, and optionally, an activator.

36. The method of claim 35, wherein the process produces a mixture of 1-hexene and 1-octene

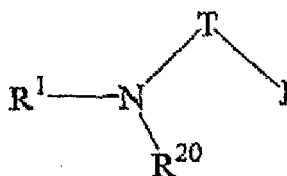
37. The method of claim 36 wherein the reaction occurs in a hydrocarbon solvent.

55 38. The method of claim 37 wherein the reaction occurs in an aliphatic hydrocarbon solvent.

Patentansprüche

1. Verfahren zur Herstellung von Olefinoligomeren, bei dem ein Olefin mit einem Katalysator umgesetzt wird, wobei die Oligomerisierungsreaktion eine Selektivität von mindestens 70 Mol% für das Oligomer aufweist und wobei der Katalysator aus der Kombination von:

(1) einem Liganden der **dadurch** die folgende allgemeine Formel wiedergegeben wird:



in der R^1 und R^{20} jeweils unabhängig ausgewählt sind aus der Gruppe bestehend aus Wasserstoff und gegebenenfalls substituiertem Kohlenwasserstoff, Heteroatom-enhaltenden Kohlenwasserstoff und Silyl, mit der Maßgabe, dass R^1 oder R^{20} nicht gleich T-J sind, wobei T-J wie in der obigen allgemeinen Formel angegeben und unten definiert sind;

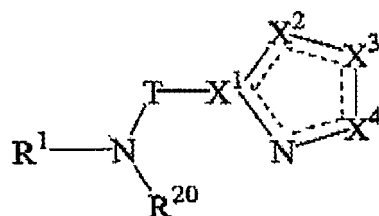
T eine verbrückende Gruppe der allgemeinen Formel $-(T^1R^2R^3)-$ ist, in der T^1 ausgewählt ist aus der Gruppe bestehend aus Kohlenstoff und Silizium, R^2 und R^3 jeweils unabhängig ausgewählt sind aus der Gruppe bestehend aus Wasserstoff, Halogen, und gegebenenfalls substituiertem Alkyl, Heteroalkyl, Aryl, Heteroaryl, Alkoxy, Aryloxy, Silyl, Boryl, Phosphino, Amino, Alkylthio, Arylthio und Kombinationen davon, mit der Maßgabe, dass zwei oder mehr R^2 - und/oder R^3 -Gruppen zusammengefügt sein können, um einen oder mehrere gegebenenfalls substituierte Ringsysteme mit 3 bis 50 Nicht-Wasserstoffatomen sind;

J ein gegebenenfalls substituiertes fünfgliedriger Heterozyklus ist, der mindestens ein Stickstoffatom als Teil des Rings aufweist, mit der weiteren Maßgabe, dass zwei oder mehrere R^2 - und/oder R^3 -Gruppen zur Bildung eines oder mehrerer gegebenenfalls substituiertes Ringsysteme mit 3-50 Nicht-Wasserstoffatomen zusammengefügt sein können;

(2) eine Metallvorläuferbindung, die durch die allgemeine Formel $Cr(L)_n$ wiedergegeben wird, wobei jedes L unabhängig ausgewählt ist aus der Gruppe bestehend aus Halogenid, Alkyl, substituiertem Alkyl, Cycloalkyl, substituiertem Cycloalkyl, Heteroalkyl, substituiertem Heteroalkyl, Heterocycloalkyl, substituiertem Heterocycloalkyl, Aryl, substituiertem Aryl, Heteroaryl, substituiertem Heteroaryl, Alkoxy, Aryloxy, Hydroxy, Boryl, Silyl, Amino, Amin, Hydrido, Allyl, Dien, Seleno, Phosphino, Phosphin, Ether, Thioether, Carboxylaten, Thio, 1,3-dionaten, Oxalaten, Karbonaten, Nitraten, Sulfaten, Ethern, Thioethern und Kombinationen davon, wobei zwei oder mehrere L-Gruppen in einer Ringstruktur mit von 3 bis 50 Nicht-Wasserstoffatomen kombiniert sein können; n 1, 2, 3, 4, 5 oder 6 ist, und

(3) gegebenenfalls einen oder mehreren Aktivatoren gebildet ist.

2. Verfahren nach Anspruch 1, bei dem der Ligand durch die folgenden allgemeine Formel wiedergegeben wird:



in der R^1 , R^{20} , und T wie oben beschrieben sind; und X^1 Stickstoff oder $-C(R^8)_n-$, X^2 , X^3 und X^4 ausgewählt sind aus der Gruppe bestehend aus Sauerstoff, Schwefel, $-C(R^8)_n-$, $-N(R^8)_n-$ und mit der Maßgabe, dass X^1 $-C(R^8)_n-$ oder mindestens einer von X^2 , X^3 oder X^4 $-C(R^8)_n-$ ist, jedes n 1 oder 2 und jedes n 0 oder 1 ist; und jedes R^8 unabhängig ausgewählt ist aus der Gruppe bestehend aus Wasserstoff, Halogen, Nitro, und gegebenenfalls substituiertem Alkyl, Heteroalkyl, Aryl, Heteroaryl, Alkoxy, Aryloxy, Silyl, Boryl, Phosphino, Amino, Alkylthio, Arylthio,

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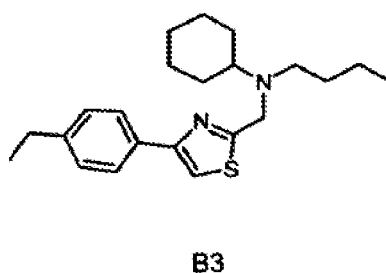
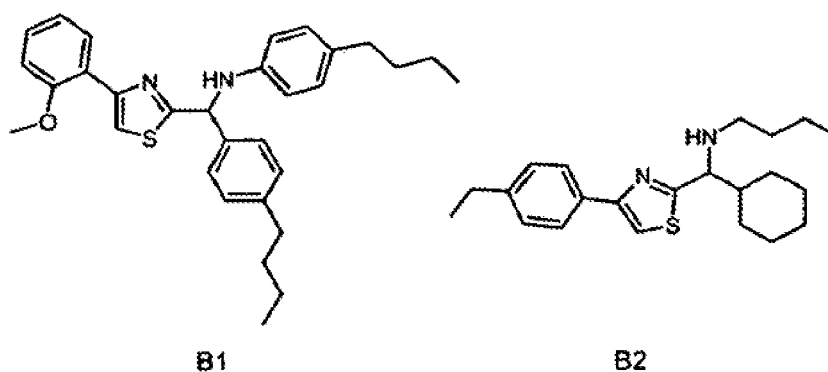
und Kombinationen davon, und gegebenenfalls zwei oder mehr R¹-, R²⁰-, R²-, R³- und R⁸-Gruppen zur Bildung eines oder mehrerer gegebenenfalls substituierter Ringsysteme zusammengefügt sein können.

3. Verfahren nach Anspruch 1, bei dem R¹ und R²⁰ jeweils unabhängig ausgewählt sind aus Wasserstoff und gegebenenfalls substituiertem Alkyl, Heteroalkyl, Aryl, Heteroaryl, Silyl und Kombinationen davon.

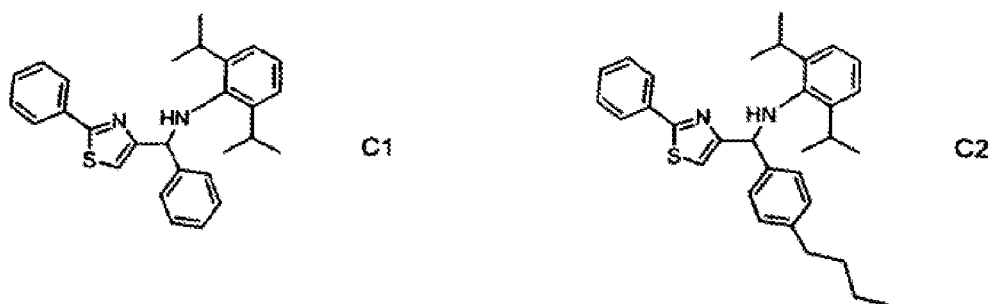
4. Verfahren nach Anspruch 2, bei dem R¹ und R²⁰ jeweils unabhängig ausgewählt sind aus Wasserstoff und gegebenenfalls substituiertem Alkyl, Heteroalkyl, Aryl, Heteroaryl, Silyl und Kombinationen davon.

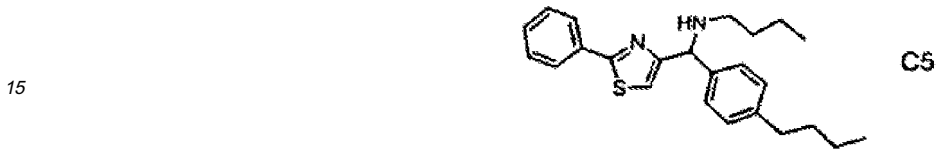
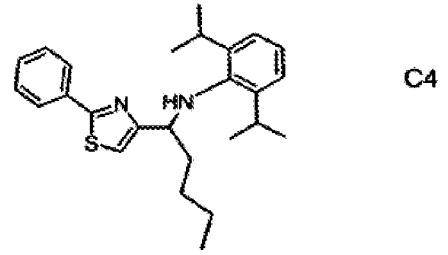
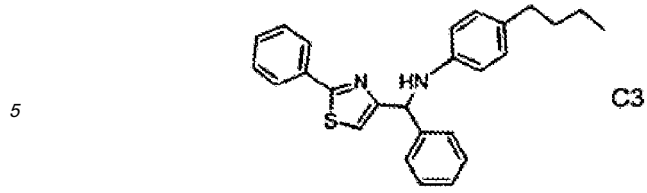
5. Verfahren nach Anspruch 2, bei dem R¹ Wasserstoff ist und R²⁰ ausgewählt ist aus gegebenenfalls substituiertem Alkyl, Heteroalkyl, Cycloalkyl, Heterocycloalkyl, Silyl und Kombinationen davon.

6. Verfahren nach Anspruch 1, bei dem der Ligand umfasst:

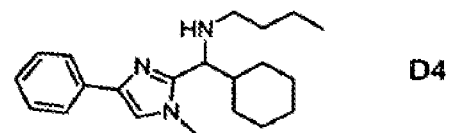
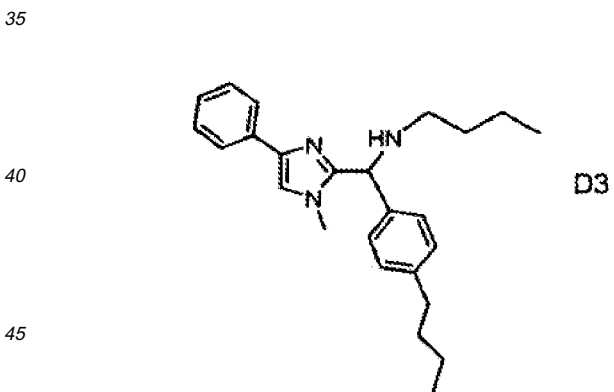
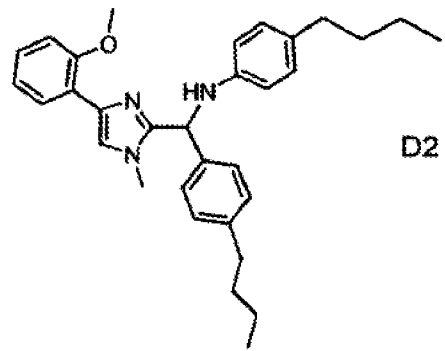
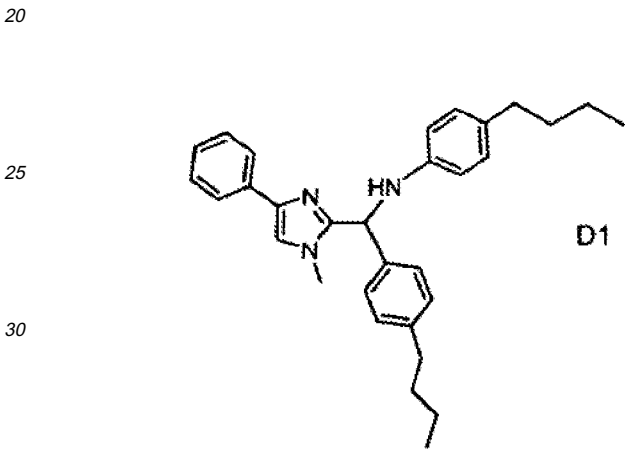


7. Verfahren nach Anspruch 1, bei dem der Ligand ausgewählt ist aus der Gruppe bestehend aus:





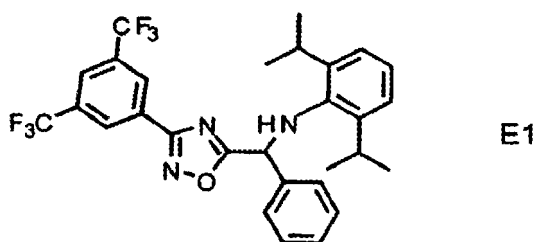
8. Verfahren nach Anspruch 1, bei dem der Ligand ausgewählt ist aus der Gruppe bestehend aus:



9. Verfahren nach Anspruch 1, bei dem der Ligand umfasst:

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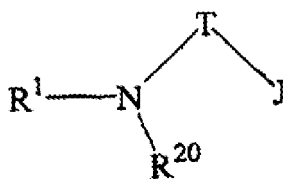
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10. Verfahren nach einem der Ansprüche 1 bis 9, bei dem der Aktivator ein Alumoxan ist, das gegebenenfalls in jeglicher Kombination mit Gruppe-13-Reagentien, divalenten Metall-Reagenzien oder Alkalimetall-Reagenzien verwendet werden kann.
- 20
11. Verfahren nach einem der Ansprüche 1 bis 9, bei dem der Aktivator ein neutraler oder ionisch stöchiometrischer Aktivator ist, der gegebenenfalls in jeglicher Kombination mit Gruppe-13-Reagentien, divalenten Metall-Reagenzien oder Alkalimetall-Reagenzien verwendet werden kann.
- 25
12. Verfahren nach einem der Ansprüche 1 bis 9, bei dem der Aktivator ausgewählt ist aus der Gruppe bestehend aus modifiziertem Methylalumoxan (MMAO), Methylaluminoxan (MAO), Trimethylaluminium (TMA), Triisobutylaluminium (TIBA), Diisobutylaluminiumhydrid (DIBAL), Polymethylaluminoxan-IP (PMAO), Triphenylcarbonium-tetrakis(perfluorophenyl)borat, N,N-Dimethyl-anilinium-tetrakis(perfluorophenyl)borat, N,N-Di(n-decyl)-4-n-butyl-anilinium-tetrakis(perfluorophenyl)borat und Mischungen davon.
- 30
13. Verfahren nach einem der Ansprüche 1 bis 9, bei dem Metallvorläufer ausgewählt ist aus der Gruppe bestehend aus $(\text{THF})_3\text{CrMeCl}_2$, $(\text{THF})_3\text{CrCl}_3$, $(\text{Mes})_3\text{Cr}(\text{THF})$, $[(\text{TFA})_2\text{Cr}(\text{OEt}_2)]_2$, $(\text{THF})_3\text{Cr}(\eta^2\text{-}2,2\text{biphenyl})\text{Br}$, $(\text{THF})_3\text{CrPh}_3$ und Mischungen davon.
- 35
14. Verfahren nach Anspruch 1, bei dem das Olefin ein C_2 - bis C_{12} -Olefin ist.
15. Verfahren nach Anspruch 1, bei dem das Olefin ein C_2 - bis C_8 -Olefin ist.
- 40
16. Verfahren nach Anspruch 1, bei dem das Olefin Ethylen ist.
17. Verfahren nach Anspruch 16, bei dem das Verfahren ein Trimer oder ein Tetramer des Olefins bildet.
18. Verfahren nach Anspruch 17, bei dem das Verfahren 1-Hexen bildet.
- 45
19. Verfahren nach Anspruch 17, bei dem das Verfahren 1-Okten bildet.
20. Verfahren nach Anspruch 16, wobei das Verfahren eine Mischung von 1-Hexen und 1-Okten bildet.
- 50
21. Verfahren nach Anspruch 1, bei dem die Reaktion in einem Kohlenwasserstoff-Lösungsmittel stattfindet.
22. Verfahren nach Anspruch 21, bei dem die Reaktion in einem aliphatischen Kohlenwasserstoff-Lösungsmittel stattfindet.
23. Zusammensetzung, umfassend:

(1) ein Ligand der **dadurch** die folgende allgemeine Formel charakterisiert ist:

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10 in der R^1 und R^{20} jeweils unabhängig ausgewählt sind aus der Gruppe bestehend aus Wasserstoffen und gegebenenfalls substituiertem Kohlenwasserstoff, Heteroatom-enhaltenden Kohlenwasserstoff und Silyl, vorausgesetzt, dass R^1 oder R^{20} nicht gleich T-J sind, wobei T-J wie in der obigen allgemeinen Formel angegeben und unten definiert sind;

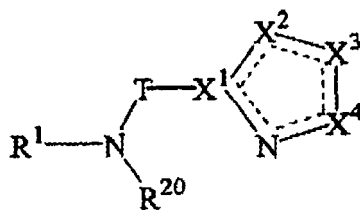
15 T eine verbrückende Gruppe der allgemeinen Formel $-(T'R^2R^3)-$ ist, in der T' ausgewählt ist aus der Gruppe bestehend aus Kohlenstoff und Silizium, R^2 und R^3 jeweils unabhängig ausgewählt sind von der Gruppe bestehend aus Wasserstoff, Halogen, und gegebenenfalls substituiertem Alkyl, Heteroalkyl, Aryl, Heteroaryl, Alkoxy, Aryloxy, Silyl, Boryl, Phosphino, Amino, Alkylthio, Arylthio und Kombinationen davon, mit der Maßgabe, dass zwei oder mehr R^2 - und/oder R^3 -Gruppen zusammengefügt sein können, um einen oder mehrere gegebenenfalls substituierte Ringsysteme mit 3 bis 50 Nicht-Kohlenwasserstoffatomen sind;

20 J ein gegebenenfalls substituierter fünfgliedriger Heterozyklus ist, der mindestens ein Stickstoffatom als Teil des Rings enthält, mit der weiteren Maßgabe, dass J mindestens zwei, jedoch nicht mehr als vier Heteroatome enthält;

25 (2) eine Metallvorläuferbindung, die durch die allgemeine Formel $Cr(L)_n$ wiedergegeben wird, wobei jedes L unabhängig ausgewählt ist aus der Gruppe bestehend aus Halogenid, Alkyl, substituiertem Alkyl, Cycloalkyl, substituiertem Cycloalkyl, Heteroalkyl, substituiertem Heteroalkyl, Heterocycloalkyl, substituiertem Heterocycloalkyl, Aryl, substituiertem Aryl, Heteroaryl, substituiertem Heteroaryl, Alkoxy, Aryloxy, Hydroxy, Boryl, Silyl, Amino, Amin, Hydrido, Allyl, Dien, Seleno, Phosphino, Phosphin, Ether, Thioether, Carboxylaten, Thio, 1,3-dionaten, Oxalate, Karbonaten, Nitraten, Sulfaten, Ethern, Thioethern und Kombinationen davon, wobei zwei oder mehrere L-Gruppen in einer Ringstruktur mit von 3 bis 50 Nicht-Wasserstoffatomen kombiniert sein können; n 1, 2, 3, 4, 5 oder 6 ist, und

30 (3) gegebenenfalls einen oder mehreren Aktivatoren.

35 **24.** Zusammensetzung nach Anspruch 23, bei dem der Ligand durch die folgende allgemeine Formel wiedergegeben wird:



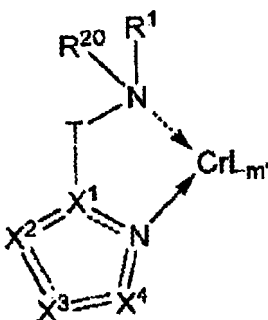
45 in der R^1 , R^{20} , und T wie oben beschrieben sind; und X^1 Stickstoff oder $-C(R^8)_n$ -, X^2 , X^3 und X^4 ausgewählt sind aus der Gruppe bestehend aus Sauerstoff, Schwefel, $-C(R^8)_n$ -, $-N(R^8)_n$ - und mit der Maßgabe, dass X^1 $-C(R^8)_n$ - oder mindestens einer von X^2 , X^3 oder X^4 $-C(R^8)_n$ - ist,

50 jedes n^1 1 oder 2 und jedes n^2 0 oder 1 ist; und jedes R^8 unabhängig ausgewählt ist aus der Gruppe bestehend aus Wasserstoff, Halogen, Nitro, und gegebenenfalls substituiertem Alkyl, Heteroalkyl, Aryl, Heteroaryl, Alkoxy, Aryloxy, Silyl, Boryl, Phosphino, Amino, Alkylthio, Arylthio, und Kombinationen davon, und gegebenenfalls zwei oder mehr R^1 -, R^{20} -, R^2 -, R^3 - und R^8 -Gruppen zur Bildung eines oder mehrerer gegebenenfalls substituierter Ringsysteme zusammengefügt sein können.

55 **25.** Ein Metallkomplex, der durch die folgende allgemeine Formel wiedergegeben wird:

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bei dem R^1 und R^{20} jeweils unabhängig ausgewählt sind aus der Gruppe bestehend aus Wasserstoffen und gegebenenfalls substituiertem Alkyl, Heteroalkyl, Cycloalkyl, Heterocycloalkyl, Aryl, Heteroaryl, Silyl und Kombinationen davon;

20

X^1 Stickstoff oder $-C(R^8)_n$ -, X^2 , X^3 und X^4 jeweils unabhängig ausgewählt sind aus der Gruppe bestehend aus Sauerstoff, Schwefel, $-C(R^8)_n$ - oder $-N(R^8)_n$ -, wobei jedes n^1 1 oder 2 und jedes n^2 0 oder 1 ist und jedes R^8 jeweils unabhängig ausgewählt ist aus der Gruppe bestehend aus Wasserstoff, Halogen, Nitro, und gegebenenfalls substituiertem Alkyl, Heteroalkyl, Aryl, Heteroaryl, Alkoxy, Aryloxy, Silyl, Boryl, Phosphino, Amino, Alkylthio, Arylthio, und Kombinationen davon, mit der Maßgabe, dass mindestens einer aber nicht mehr als 3 von X^1 , X^2 , X^3 und X^4 ein Heteroatom ist;

25

T eine verbrückende Gruppe der allgemeinen Formel $-(T^1R^2R^3)-$ ist, wobei T' ausgewählt ist aus der Gruppe bestehend aus Kohlenstoff und Silizium, R^2 und R^3 jeweils unabhängig ausgewählt sind aus der Gruppe bestehend aus Wasserstoff, Halogen und gegebenenfalls substituiertem Alkyl, Heteroalkyl, Aryl, Heteroaryl, Alkoxy, Aryloxy, Silyl, Boryl, Phosphino, Amino, Alkylthio, Arylthio und Kombinationen davon, mit der Maßgabe, dass zwei oder mehr R^2 - und/oder R^3 -Gruppen zusammengefügt sein können, um einen oder mehrere gegebenenfalls substituierte Ringsysteme mit 3 bis 50 Nicht-Wasserstoffatomen zu bilden, wobei jede Kombination von 2 oder mehreren R^1 -, R^2 -, R^3 -, und/oder R^8 -Gruppen zusammengefügt sein können, um eine oder mehrere optional substituierte, zusammengefügte Ringsysteme zu bilden;

30

jedes L ist unabhängig ausgewählt aus der Gruppe bestehend aus Halogenid, Alkyl, substituiertem Alkyl, Cycloalkyl, substituiertem Cycloalkyl, Heteroalkyl, substituiertem Heteroalkyl, Heterocycloalkyl, substituiertem Heterocycloalkyl, Aryl, substituiertem Aryl, Heteroaryl, substituiertem Heteroaryl, Alkoxy, Aryloxy, Hydroxy, Boryl, Silyl, Amino, Amin, Hydrido, Allyl, Dien, Seleno, Phosphino, Phosphin, Ether, Thioether, Carboxylaten, Thio, 1,3-dionaten, Oxalaten, Karbonaten, Nitraten, Sulfaten, Ethern, Thioethern und Kombinationen davon, wobei zwei oder mehrere L-Gruppen in einer Ringstruktur mit von 3 bis 50 Nicht-Wasserstoffatomen kombiniert sein können;

35

m^1 1, 2 oder 3 ist; und

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ein gepunkteter Pfeil andeutet, dass die koordinative Bindung eine optionale Bindung ist, die vorhanden sein kann oder nicht.

26. Komplex nach Anspruch 25, bei dem R^8 gegebenenfalls substituiertes Aryl oder Heteroaryl ist und R^8 und M gegebenenfalls zusammengefügt sein können zur Bildung eines Metallazyklus.

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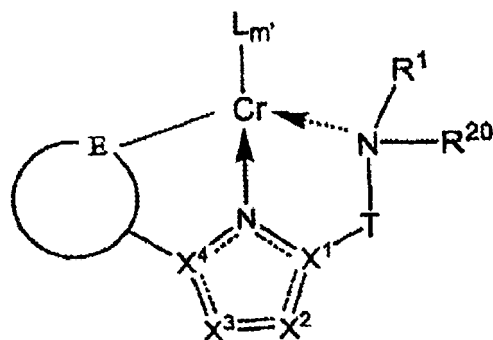
27. Metallkomplex, der durch die folgende allgemeine Formel wiedergegeben wird:

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in der R^1 und R^{20} jeweils unabhängig ausgewählt sind aus der Gruppe bestehend aus Wasserstoffen und gegebenenfalls substituiertem Alkyl, Heteroalkyl, Cycloalkyl, Heterocycloalkyl, Aryl, Heteroaryl, Silyl und Kombinationen davon;

20

X^1 Stickstoff oder $-C(R^8)_n-$, X^2 , X^3 und X^4 jeweils unabhängig ausgewählt sind aus der Gruppe bestehend aus Sauerstoff, Schwefel, $-C(R^8)_n-$ oder $-N(R^8)_n-$, wobei jedes n' 1 oder 2 und jedes n'' 0 oder 1 ist und jedes R^8 jeweils unabhängig ausgewählt ist aus der Gruppe bestehend aus Wasserstoff, Halogen, Nitro, und gegebenenfalls substituiertem Alkyl, Heteroalkyl, Aryl, Heteroaryl, Alkoxy, Aryloxy, Silyl, Boryl, Phosphino, Amino, Alkylthio, Arylthio, und Kombinationen davon, mit der Maßgabe, dass mindestens einer aber nicht mehr als 3 von X^1 , X^2 , X^3 und X^4 ein Heteroatom ist;

25

T eine verbrückende Gruppe der allgemeinen Formel $-(T'R^2R^3)-$ ist, wobei T' ausgewählt ist aus der Gruppe bestehend aus Kohlenstoff und Silizium, R^2 und R^3 jeweils unabhängig ausgewählt sind aus der Gruppe bestehend aus Wasserstoff, Halogen, und gegebenenfalls substituiertem Alkyl, Heteroalkyl, Aryl, Heteroaryl, Alkoxy, Aryloxy, Silyl, Boryl, Phosphino, Amino, Alkylthio, Arylthio und Kombinationen davon, mit der Maßgabe, dass zwei oder mehr R^2 - und/oder R^3 -Gruppen zusammengefügt sein können, um einen oder mehrere gegebenenfalls substituierte Ringsysteme mit 3 bis 50 Nicht-Kohlenwasserstoffatomen zu bilden, wobei jede Kombination von 2 oder mehreren R^1 -, R^2 -, R^3 -, und/oder R^8 -Gruppen zusammengefügt sein, um eine oder mehrere optional substituierte, zusammengefügte Ringsystem zu bilden;

30

jedes L ist unabhängig ausgewählt aus der Gruppe bestehend aus Halogenid, Alkyl, substituiertem Alkyl, Cycloalkyl, substituiertem Cycloalkyl, Heteroalkyl, substituiertem Heteroalkyl, Heterocycloalkyl, substituiertem Heterocycloalkyl, Aryl, substituiertem Aryl, Heteroaryl, substituiertem Heteroaryl, Alkoxy, Aryloxy, Hydroxy, Boryl, Silyl, Amino, Amin, Hydrido, Allyl, Dien, Seleno, Phosphino, Phosphin, Ether, Thioether, Carboxylaten, Thio, 1,3-dionaten, Oxalaten, Karbonaten, Nitraten, Sulfaten, Ethern, Thioethern und Kombinationen davon, wobei zwei oder mehrere L-Gruppen in einer Ringstruktur mit von 3 bis 50 Nicht-Wasserstoffatomen kombiniert sein können; m' 1, 2 oder 3 ist;

35

E ein Kohlenstoffatom ist, das Teil eines gegebenenfalls substituierten Aryl- oder Heteroarylringes ist; und ein gepunkteter Pfeil andeutet, dass die koordinative Bindung eine optionale Bindung ist, die vorhanden sein kann oder nicht.

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28. Komplex nach Anspruch 27, wobei der Komplex durch die Formel:

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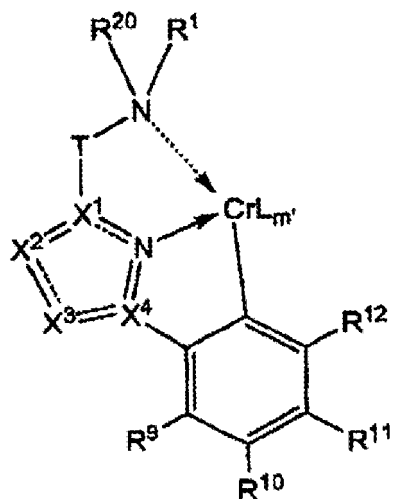
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wiedergegeben wird, in der

R^1 , R^{20} , X^1 , X^2 , X^3 , X^4 , L , T und m' wie oben definiert sind;

R^9 , R^{10} , R^{11} und R^{12} jeweils unabhängig ausgewählt sind aus der Gruppe bestehend aus Wasserstoff, Halogen, Nitro, und gegebenenfalls substituiertem Alkyl, Heteroalkyl, Aryl, Heteroaryl, Alkoxy, Aryloxy, Silyl, Boryl, Phosphino, Amino, Alkylthio, Arylthio und Kombinationen davon, mit der Maßgabe, dass gegebenenfalls zwei oder mehrere

25

der R^9 , R^{10} , R^{11} und R^{12} zusammen gefügt sein können zur Bildung einer oder mehrerer gegebenenfalls substituierter, zusammengefügt Ringsysteme;

ein gepunkteter Pfeil andeutet, dass die koordinative Bindung eine optionale Bindung ist, die vorhanden sein kann oder nicht.

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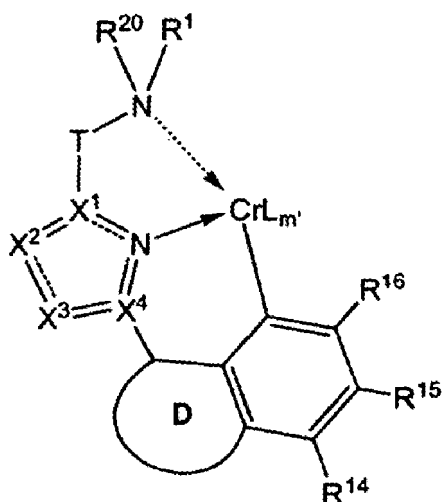
29. Komplex nach Anspruch 27, wobei der Komplex durch die Formel:

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wiedergegeben wird, in der

R^1 , R^{20} , X^1 , X^2 , X^3 , X^4 , L , T und m' wie oben definiert sind;

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R^{14} , R^{15} und R^{16} jeweils unabhängig ausgewählt sind aus der Gruppe bestehend aus Wasserstoff, Halogen, Nitro, und gegebenenfalls substituiertem Alkyl, Heteroalkyl, Aryl, Heteroaryl, Alkoxy, Aryloxy, Silyl, Boryl, Phosphino, Amino, Alkylthio, Arylthio und Kombinationen davon, mit der Maßgabe, dass gegebenenfalls zwei oder mehrere von R^{14} , R^{15} und R^{16} zur Bildung eines oder mehrerer gegebenenfalls substituierter, zusammengefügt Ringsy-

steme zusammen gefügt sein können;

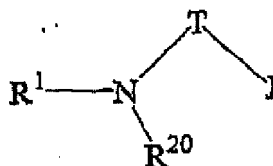
D ein Ring ausgewählt aus der Gruppe bestehend aus gegebenenfalls substituiertem Aryl und Heteroaryl; und ein gepunkteter Pfeil andeutet, dass die koordinative Bindung eine optionale Bindung ist, die vorhanden sein kann oder nicht.

- 5
30. Verfahren zur Herstellung von Olefinoligomeren, bei dem eine Olefin mit einem Katalysator unter Oligomersationsbedingungen umgesetzt wird, bei dem die Oligomerisationsreaktion eine Selektivität von mindestens 70 Mol% des Oligomers aufweist und wobei der Katalysator ausgewählt aus einem der Ansprüche 25 bis 29 und gegebenenfalls einem Aktivator ist.
- 10
31. Verfahren nach Anspruch 30, bei dem das Olefin Ethylen ist.
32. Verfahren nach Anspruch 31, wobei das Verfahren ein Trimer oder Tetramer des Olefins bildet.
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33. Verfahren nach Anspruch 32, wobei das Verfahren 1-Hexen bildet.
34. Verfahren nach Anspruch 32, wobei das Verfahren 1-Okten bildet.
- 20
35. Verfahren zur Herstellung von Olefinoligomeren, bei dem ein Olefin mit einem Katalysator umgesetzt wird, wobei die Oligomerisationsreaktion zwei Oligomere bildet, wobei die kombinierte Selektivität der zwei Oligomere in Summe mindestens 70 Mol% bildet, und wobei der Katalysator aus den Metallkomplexen ausgewählt aus einem der Ansprüche 23 bis 29 und gegebenenfalls einem Aktivator besteht.
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36. Verfahren nach Anspruch 35, wobei das Verfahren eine Mischung aus 1-Hexen und 1-Okten bildet.
37. Verfahren nach Anspruch 36, wobei die Reaktion in einem Kohlenwasserstoff-Lösungsmittel stattfindet.
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38. Verfahren nach Anspruch 37, wobei die Reaktion in einem aliphatischen Kohlenwasserstoff-Lösungsmittel stattfindet.

Revendications

- 35
1. Procédé de production d'oligomères d'oléfines, comprenant le fait de faire réagir une oléfine avec un catalyseur, dans lequel ladite réaction d'oligomérisation possède une sélectivité d'au moins 70 pour cent en moles pour l'oligomère, et dans lequel ledit catalyseur est formé de la combinaison :

(1) d'un ligand **caractérisé par** la formule générale suivante :



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dans laquelle R¹ et R²⁰ sont chacun choisis indépendamment dans le groupe constitué par un atome d'hydrogène et un groupe hydrocarbyle éventuellement substitué, hydrocarbyle contenant un hétéroatome et silyle, à condition que R¹ ou R²⁰ ne représentent pas T-J, où T-J est tel qu'indiqué par la formule générale ci-dessus et défini ci-dessous ;

50

T représente un groupe pontant de formule générale -(T'R²R³)-, où T' est choisi dans le groupe constitué par le carbone et le silicium, R² et R³ sont choisis indépendamment dans le groupe constitué par un atome d'hydrogène ou d'halogène, et un groupe alkyle, hétéroalkyle, aryle, hétéroaryle, alcoxy, aryloxy, silyle, boryle, phosphino, amino, alkylthio, arylthio, éventuellement substitué, et leurs combinaisons, à condition qu'au moins deux groupes R² et/ou R³ puissent être reliés l'un à l'autre pour former un ou plusieurs systèmes cycliques éventuellement substitués comportant de 3-50 atomes autres que l'hydrogène ;

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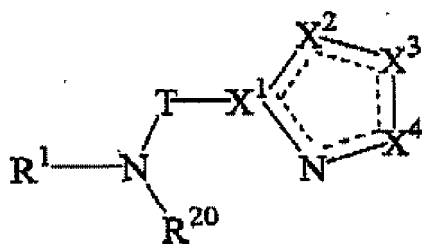
J représente un hétérocycle à cinq chaînons éventuellement substitué, contenant au moins un atome d'azote

faisant partie du noyau, à condition par ailleurs que J contienne au moins deux, mais pas plus de quatre, hétéroatomes ;

(2) d'un composé précurseur de métal **caractérisé par** la formule générale $Cr(L)_n$, où chaque symbole L est choisi indépendamment dans le groupe constitué par un halogénure ou un groupe alkyle, alkyle substitué, cycloalkyle, cycloalkyle substitué, hétéroalkyle, hétéroalkyle substitué, hétérocycloalkyle, hétérocycloalkyle substitué, aryle, aryle substitué, hétéroaryle, hétéroaryle substitué, alcoxy, aryloxy, hydroxy, boryle, silyle, amino, amine, hydruro, allyle, diène, séléno, phosphino, phosphine, éther, thioéther, les carboxylates, thio, les 1,3-dionates, les oxalates, les carbonates, les nitrates, les sulfates, les éthers, les thioéthers et leurs combinaisons, dans lequel au moins deux groupes L peuvent être combinés en une structure cyclique comportant de 3 to 50 atomes autres que l'hydrogène ; n est égal à 1, 2, 3, 4, 5 ou 6 ; et

(3) éventuellement, d'un ou plusieurs activateurs.

2. Procédé selon la revendication 1, dans lequel le ligand est **caractérisé par** la formule générale suivante :



dans laquelle R^1 , R^{20} et T sont décrits ci-dessus ; et X^1 représente un atome d'azote ou un groupe $-C(R^8)_{n'}$, X^2 , X^3 et X^4 sont choisis dans le groupe constitué par l'oxygène, le soufre, $-C(R^8)_{n'}$, $-N(R^8)_{n'}$, et à condition que X^1 représente $-C(R^8)_{n'}$ ou qu'au moins un des symboles X^2 , X^3 ou X^4 représente $-C(R^8)_{n'}$; chaque n' est égal à 1 ou 2 et chaque n'' est égal à 0 ou 1 ; et

chaque symbole R^8 est choisi indépendamment dans le groupe constitué par un atome d'hydrogène ou d'halogène ou un groupe nitro et un groupe alkyle, hétéroalkyle, aryle, hétéroaryle, alcoxy, aryloxy, silyle, boryle, phosphino, amino, alkylthio, arylthio, éventuellement substitué, et leurs combinaisons, et éventuellement au moins deux groupes R^1 , R^{20} , R^2 , R^3 et R^8 peuvent être reliés pour former un ou plusieurs systèmes cycliques éventuellement substitués.

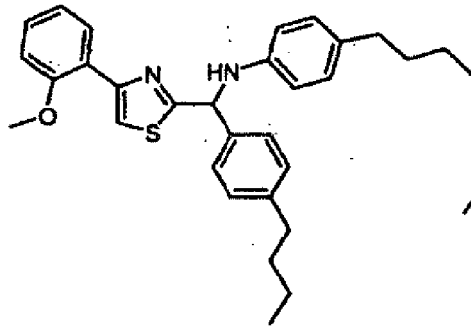
3. Procédé selon la revendication 1, dans lequel R^1 et R^{20} sont chacun choisis indépendamment parmi un atome d'hydrogène et un groupe alkyle, hétéroalkyle, aryle, hétéroaryle, silyle, éventuellement substitué, et leurs combinaisons.

4. Procédé selon la revendication 2, dans lequel R^1 et R^{20} sont chacun choisis indépendamment parmi un atome d'hydrogène et un groupe alkyle, hétéroalkyle, aryle, hétéroaryle, silyle, éventuellement substitué, et leurs combinaisons.

5. Procédé selon la revendication 2, dans lequel R^1 représente un atome d'hydrogène et R^{20} est choisi parmi un groupe alkyle, hétéroalkyle, cycloalkyle, hétérocycloalkyle, silyle, éventuellement substitué, et leurs combinaisons.

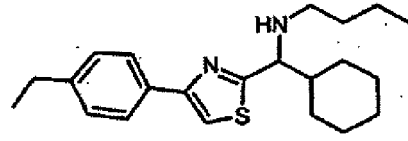
6. Procédé selon la revendication 1, dans lequel le ligand comprend :

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B1

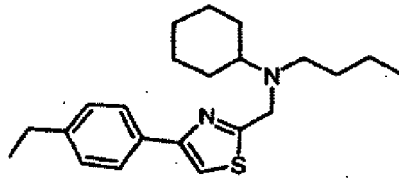
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B2

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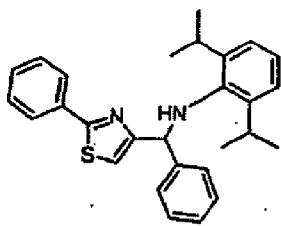


B3

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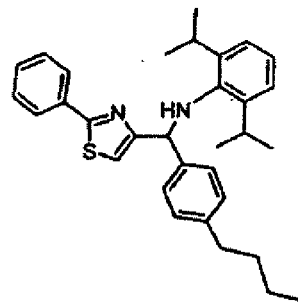
7. Procédé selon la revendication 1, dans lequel le ligand est choisi dans le groupe constitué par :

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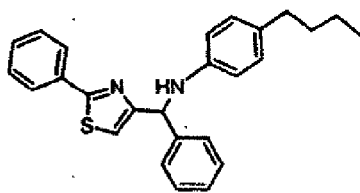
C1

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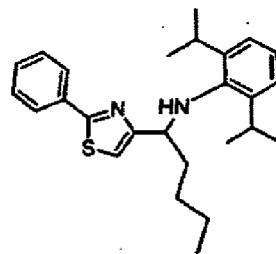
C2

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C3

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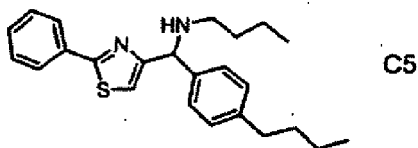


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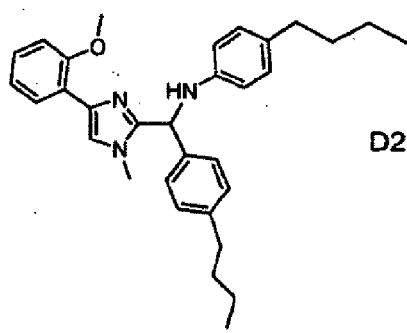
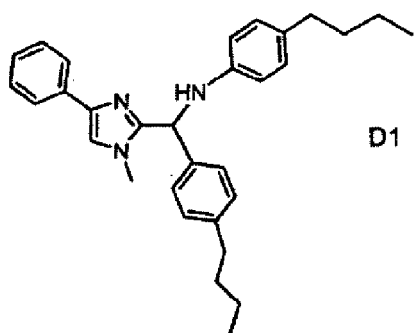
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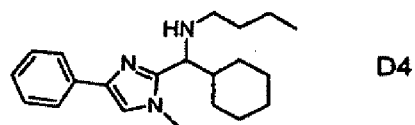
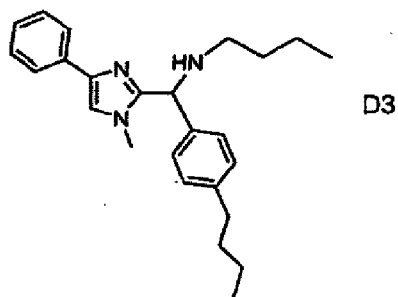
8. Procédé selon la revendication 1, dans lequel le ligand est choisi dans le groupe constitué par :

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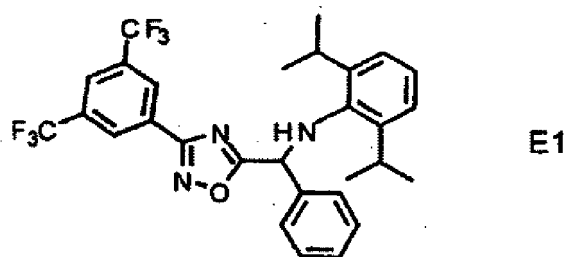


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9. Procédé selon la revendication 1, dans lequel le ligand comprend

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10. Procédé selon l'une quelconque des revendications 1 à 9, dans lequel l'activateur est un alumoxane, qui peut éventuellement être utilisé en toute combinaison avec des réactifs du groupe 13, des réactifs à base de métaux divalents ou des réactifs à base de métaux alcalins.

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11. Procédé selon l'une quelconque des revendications 1 à 9, dans lequel l'activateur est un activateur stoechiométrique neutre ou ionique, qui peut éventuellement être utilisé en toute combinaison avec des réactifs du groupe 13, des réactifs à base de métaux divalents ou des réactifs à base de métaux alcalins.

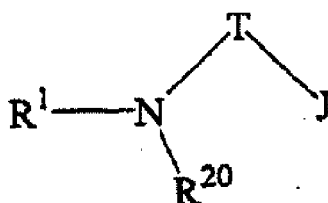
12. Procédé selon l'une quelconque des revendications 1 à 9, dans lequel l'activateur est choisi dans le groupe constitué

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par un méthylalumoxane modifié (MMAO), le méthylalumoxane (MAO), le triméthylaluminium (TMA), le triisobutylaluminium (TIBA), l'hydrure de diisobutylaluminium (DIBAL), le polyméthylalumoxane-IP (PMAO), le tétrakis(perfluorophényl)borate de triphénylcarbonium, le tétrakis(perfluorophényl)borate de N,N-diméthylanilinium, le tétrakis(perfluorophényl)-borate de N,N-di(n-décyl)-4-n-butyl-anilinium, et leurs mélanges.

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13. Procédé selon l'une quelconque des revendications 1 à 9, dans lequel le précurseur de métal est choisi dans le groupe constitué par $(\text{THF})_3\text{CrMeCl}_2$, $(\text{THF})_3\text{CrCl}_3$, $(\text{Mes})_3\text{Cr}(\text{THF})$, $[\text{TFA}]_2\text{Cr}(\text{OEt}_2)_2$, $(\text{THF})_3\text{Cr}(\eta^2\text{-2,2-biphényl})\text{Br}$, $(\text{THF})_3\text{CrPh}_3$ et leurs mélanges.
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14. Procédé selon la revendication 1, dans lequel l'oléfine est une oléfine en C_2 à C_{12} .
15. Procédé selon la revendication 1, dans lequel l'oléfine est une oléfine en C_2 à C_8 .
16. Procédé selon la revendication 1, dans lequel l'oléfine est l'éthylène.
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17. Procédé selon la revendication 16, dans lequel le procédé produit un trimère ou un tétramère de l'oléfine.
18. Procédé selon la revendication 17, dans lequel le procédé produit du 1-hexène.
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19. Procédé selon la revendication 17, dans lequel le procédé produit du 1-octène.
20. Procédé selon la revendication 16, dans lequel le procédé produit un mélange de 1-hexène et de 1-octène.
21. Procédé selon la revendication 1, dans lequel la réaction a lieu dans un solvant hydrocarboné.
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22. Procédé selon la revendication 21, dans lequel la réaction a lieu dans un solvant hydrocarboné aliphatique.
23. Composition comprenant :

30 (1) un ligand **caractérisé par** la formule générale suivante :



dans laquelle R^1 et R^{20} sont chacun choisis indépendamment dans le groupe constitué par un atome d'hydrogène et un groupe alkyle éventuellement substitué, à condition que R^1 ou R^{20} ne représentent pas T-J, où T-J est tel qu'indiqué par la formule générale ci-dessus et défini ci-dessous ;

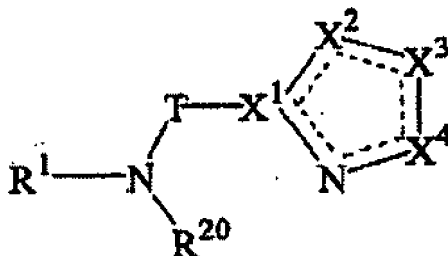
45 T représente un groupe pontant de formule générale $-(\text{T}'\text{R}^2\text{R}^3)-$, où T' est choisi dans le groupe constitué par le carbone et le silicium, R^2 et R^3 sont choisis indépendamment dans le groupe constitué par un atome d'hydrogène ou d'halogène, et un groupe alkyle, hétéroalkyle, aryle, hétéroaryle, alcoxy, aryloxy, silyle, boryle, phosphino, amino, alkylthio, arylthio, éventuellement substitué, et leurs combinaisons, à condition qu'au moins deux groupes R^2 et/ou R^3 puissent être reliés l'un à l'autre pour former un ou plusieurs systèmes cycliques éventuellement substitués comportant de 3-50 atomes autres que l'hydrogène ;

50 J représente un hétérocycle à cinq chaînons éventuellement substitué, contenant au moins un atome d'azote faisant partie du noyau, à condition par ailleurs que J contienne au moins deux, mais pas plus de quatre, hétéroatomes ;

55 (2) un composé précurseur de métal **caractérisé par** la formule générale $\text{Cr}(\text{L})_n$ où chaque symbole L est choisi indépendamment dans le groupe constitué par un halogénure ou un groupe alkyle, alkyle substitué, cycloalkyle, cycloalkyle substitué, hétéroalkyle, hétéroalkyle substitué, hétérocycloalkyle, hétérocycloalkyle substitué, aryle, aryle substitué, hétéroaryle, hétéroaryle substitué, alcoxy, aryloxy, hydroxy, boryle, silyle, amino, amine, hydruro, allyle, diène, séléno, phosphino, phosphine, éther, thioéther, les carboxylates, thio, les 1,3-dionates, les oxalates, les carbonates, les nitrates, les sulfates, les éthers, les thioéthers et leurs combinaisons, dans lequel au moins

deux groupes L peuvent être combinés en une structure cyclique comportant de 3 à 50 atomes autres que l'hydrogène ; n est égal à 1, 2, 3, 4, 5 ou 6 ; et
(3) éventuellement, un ou plusieurs activateurs.

24. Composition selon la revendication 23, dans laquelle le ligand est **caractérisé par** la formule générale suivante :

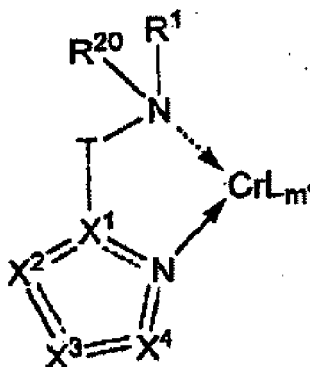


dans laquelle R^1 , R^{20} et T sont décrits ci-dessus ; et X^1 représente un atome d'azote ou un groupe $-C(R^8)_{n'}$, X^2 , X^3 et X^4 sont choisis dans le groupe constitué par l'oxygène, le soufre, $-C(R^8)_{n'}$, $-N(R^8)_{n'}$, et à condition que X^1 représente $-C(R^8)_{n'}$ ou qu'au moins un des symboles X^2 , X^3 ou X^4 représente $-C(R^8)_n$.

chaque n' est égal à 1 ou 2 et chaque n est égal à 0 ou 1 ; et,

chaque symbole R^8 est choisi indépendamment dans le groupe constitué par un atome d'hydrogène ou d'halogène ou un groupe nitro, et un groupe alkyle, hétéroalkyle, aryle, hétéroaryle, alcoxy, aryloxy, silyle, boryle, phosphino, amino, alkylthio, arylthio, éventuellement substitué, et leurs combinaisons, et éventuellement au moins deux groupes R^1 , R^{20} , R^2 , R^3 et R^8 peuvent être reliés pour former un ou plusieurs systèmes cycliques éventuellement substitués.

25. Complexe métallique **caractérisé par** la formule générale suivante :



dans laquelle R^1 et R^{20} sont chacun choisis indépendamment dans le groupe constitué par un atome d'hydrogène et un groupe alkyle, hétéroalkyle, cycloalkyle, hétérocycloalkyle, aryle, hétéroaryle, silyle, éventuellement substitué, et leurs combinaisons ;

X^1 représente un atome d'azote ou un groupe $-C(R^8)_{n'}$, X^2 , X^3 et X^4 sont choisis indépendamment dans le groupe constitué par l'oxygène, le soufre, $-C(R^8)_{n'}$ ou $-N(R^8)_{n'}$, où chaque n' est égal à 1 ou 2, et chaque n est égal à 0 ou 1, et chaque symbole R^8 est choisi indépendamment dans le groupe constitué par un atome d'hydrogène ou d'halogène ou un groupe nitro, et un groupe alkyle, hétéroalkyle, aryle, hétéroaryle, alcoxy, aryloxy, silyle, boryle, phosphino, amino, alkylthio, arylthio, éventuellement substitué, et leurs combinaisons, à condition qu'au moins un, mais pas plus de trois, des symboles X^1 , X^2 , X^3 et X^4 ne représente un hétéroatome ;

T représente un groupe pontant de formule générale $-(T'R^2R^3)-$, où T' est choisi dans le groupe constitué par le carbone et le silicium, R^2 et R^3 sont choisis indépendamment dans le groupe constitué par un atome d'hydrogène ou d'halogène, et un groupe alkyle, hétéroalkyle, aryle, hétéroaryle, alcoxy, aryloxy, silyle, boryle, phosphino, amino, alkylthio, arylthio, éventuellement substitué, et leurs combinaisons, à condition qu'au moins deux groupes R^2 et/ou R^3 puissent être reliés l'un à l'autre pour former un ou plusieurs systèmes cycliques éventuellement substitués comportant de 3-50 atomes autres que l'hydrogène ; au moins deux groupes R^1 , R^2 , R^3 et/ou R^8 , en toute combinaison, peuvent être reliés l'un à l'autre pour former un ou plusieurs systèmes à noyaux condensés éventuellement substitués ;

chaque symbole L est choisi indépendamment dans le groupe constitué par un halogénure ou les radicaux alkyle, alkyle substitué, cycloalkyle, cycloalkyle substitué, hétéroalkyle, hétéroalkyle substitué, hétérocycloalkyle, hétérocycloalkyle substitué, aryle, aryle substitué, hétéroaryle, hétéroaryle substitué, alcoxy, aryloxy, hydroxy, boryle, silyle, amino, amine, hydruro, allyle, diène, séléno, phosphino, phosphine, éther, thioéther, les carboxylates, thio,

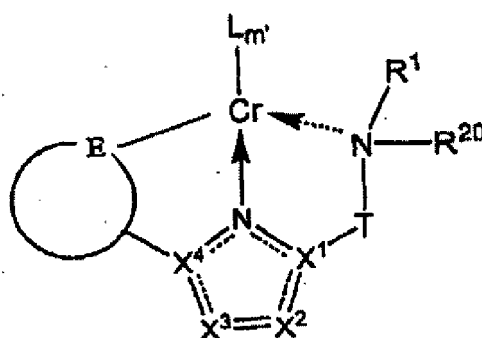
les 1,3-dionates, les oxalates, les carbonates, les nitrates, les sulfates, les éthers, les thioéthers et leurs combinaisons, dans lequel au moins deux groupes L peuvent être combinés en une structure cyclique comportant de 3 à 50 atomes autres que l'hydrogène ;

m' est égal à 1, 2 ou 3 ; et

une flèche en pointillé indique que la liaison semi-polaire est une liaison facultative pouvant ou non être présente.

26. Complexe selon la revendication 25, dans lequel R⁸ représente un groupe aryle ou hétéroaryle éventuellement substitué, et R⁸ et M sont éventuellement reliés pour former un métallocycle.

27. Complexe métallique **caractérisé par** la formule générale suivante :



dans laquelle R¹ et R²⁰ sont chacun choisis indépendamment dans le groupe constitué par un atome d'hydrogène et un groupe alkyle, hétéroalkyle, cycloalkyle, hétérocycloalkyle, aryle, hétéroaryle, silyle, éventuellement substitué, et leurs combinaisons ;

X¹ représente un atome d'azote ou un groupe -C(R⁸)_n-, X², X³ et X⁴ sont choisis indépendamment dans le groupe constitué par l'oxygène, le soufre, -C(R⁸)_n- ou -N(R⁸)_n-, où chaque n' est égal à 1 ou 2 et chaque n" est égal à 0 ou 1, et chaque symbole R⁸ est choisi indépendamment dans le groupe constitué par un atome d'hydrogène ou d'halogène ou un groupe nitro, et un groupe alkyle, hétéroalkyle, aryle, hétéroaryle, alcoxy, aryloxy, allyle, boryle, phosphino, amino, alkylthio, arylthio, éventuellement substitué, et leurs combinaisons, à condition qu'au moins un, mais pas plus de trois, des symboles X¹, X², X³ et X⁴ ne représente un hétéroatome ;

T représente un groupe pontant de formule générale -(T'R²R³)-, où T' est choisi dans le groupe constitué par le carbone et le silicium, R² et R³ sont choisis indépendamment dans le groupe constitué par un atome d'hydrogène ou d'halogène, et un groupe alkyle, hétéroalkyle, aryle, hétéroaryle, alcoxy, aryloxy, silyle, boryle, phosphino, amino, alkylthio, arylthio, éventuellement substitué, et leurs combinaisons, à condition qu'au moins deux groupes R² et/ou R³ puissent être reliés l'un à l'autre pour former un ou plusieurs systèmes cycliques éventuellement substitués comportant de 3-50 atomes autres que l'hydrogène ; au moins deux groupes R¹, R², R³ et/ou R⁸, en toute combinaison, peuvent être reliés l'un à l'autre pour former un ou plusieurs systèmes à noyaux condensés éventuellement substitués ;

chaque symbole L est choisi indépendamment dans le groupe constitué par un halogénure ou un groupe alkyle, alkyle substitué, cycloalkyle, cycloalkyle substitué, hétéroalkyle, hétéroalkyle substitué, hétérocycloalkyle, hétérocycloalkyle substitué, aryle, aryle substitué, hétéroaryle, hétéroaryle substitué, alcoxy, aryloxy, hydroxy, boryle, silyle, amino, amine, hydruro, allyle, diène, séléno, phosphino, phosphine, éther, thioéther, les carboxylates, thio, les 1,3-dionates, les oxalates, les carbonates, les nitrates, les sulfates, les éthers, les thioéthers et leurs combinaisons, dans lequel au moins deux radicaux L peuvent être combinés en une structure cyclique comportant de 3 à 50 atomes autres que l'hydrogène ; m' est égal à 1, 2 ou 3 ;

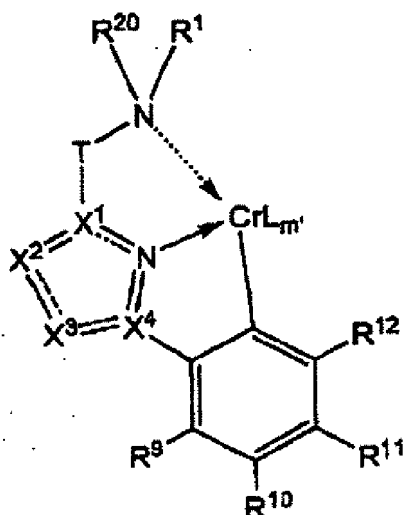
E représente un atome de carbone qui fait partie d'un noyau aryle ou hétéroaryle éventuellement substitué ; et une flèche en pointillé indique que la liaison semi-polaire est une liaison facultative pouvant ou non être présente.

28. Complexe selon la revendication 27, dans lequel le complexe est **caractérisé par** la formule :

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dans laquelle R^1 , R^{20} , X^1 , X^2 , X^3 , X^4 , L , T et m' sont tels que définis ci-dessus ;
 R^9 , R^{10} , R^{11} et R^{12} sont chacun choisis indépendamment dans le groupe constitué par un atome d'hydrogène ou d'halogène ou un groupe nitro, et un groupe alkyle, hétéroalkyle, aryle, hétéroaryle, alcoxy, aryloxy, silyle, boryle, phosphino, amino, alkylthio, arylthio, éventuellement substitué, et leurs combinaisons, à condition qu'éventuellement au moins deux des radicaux R^9 , R^{10} , R^{11} et R^{12} puissent être reliés pour former un ou plusieurs systèmes à noyaux condensés éventuellement substitués ; et
 une flèche en pointillé indique que la liaison semi-polaire est une liaison facultative pouvant ou non être présente.

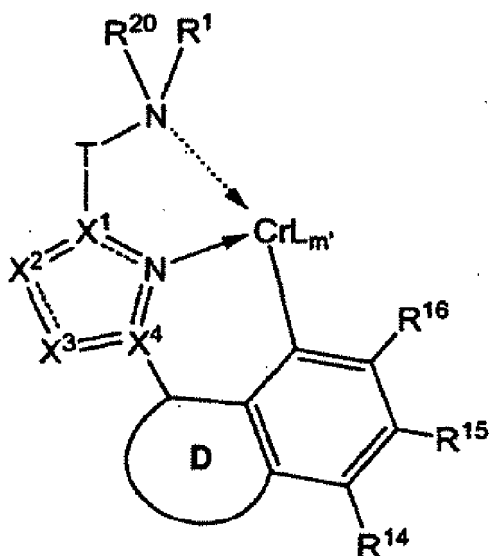
29. Complexe selon la revendication 27, dans lequel le complexe est **caractérisé** par la formule :

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dans laquelle R^1 , R^{20} , X^1 , X^2 , X^3 , X^4 , L , T et m' sont tels que définis ci-dessus ;
 R^{14} , R^{15} et R^{16} sont chacun choisis indépendamment dans le groupe constitué par un atome d'hydrogène ou d'halogène ou un groupe nitro, et un groupe alkyle, hétéroalkyle, aryle, hétéroaryle, alcoxy, aryloxy, silyle, boryle, phosphino, amino, alkylthio, arylthio, éventuellement substitué, et leurs combinaisons, à condition qu'éventuellement au moins deux des radicaux R^{14} , R^{15} et R^{16} puissent être reliés pour former un ou plusieurs systèmes à noyaux condensés éventuellement substitués ;
 D est un noyau choisi parmi des groupes aryle et hétéroaryle éventuellement substitués ; et
 une flèche en pointillé indique que la liaison semi-polaire est une liaison facultative pouvant ou non être présente.

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30. Procédé de production d'oligomères d'oléfines, comprenant le fait de faire réagir une oléfine avec un catalyseur dans des conditions d'oligomérisation, dans lequel ladite réaction d'oligomérisation possède une sélectivité d'au moins 70 pour cent en moles pour l'oligomère, et dans lequel ledit catalyseur est choisi parmi une des revendications 25 à 29, et éventuellement un activateur.

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31. Procédé selon la revendication 30, dans lequel l'oléfine est l'éthylène.

32. Procédé selon la revendication 31, dans lequel le procédé produit un trimère ou un tétramère de l'oléfine.

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33. Procédé selon la revendication 32, dans lequel le procédé produit du 1-hexène.

34. Procédé selon la revendication 32, dans lequel le procédé produit du 1-octène.

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35. Procédé de production d'oligomères d'oléfines, comprenant le fait de faire réagir une oléfine avec un catalyseur, dans lequel ladite réaction d'oligomérisation produit deux oligomères dans laquelle la sélectivité combinée des deux oligomères se monte à au moins 70 pour cent en moles, et dans lequel ledit catalyseur est constitué des complexes métalliques choisis parmi une des revendications 23 à 29, et éventuellement un activateur.

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36. Procédé selon la revendication 35, dans lequel le procédé produit un mélange de 1-hexène et de 1-octène.

37. Procédé selon la revendication 36 dans lequel la réaction a lieu dans un solvant hydrocarboné.

38. Procédé selon la revendication 37 dans lequel la réaction a lieu dans un solvant hydrocarboné aliphatique.

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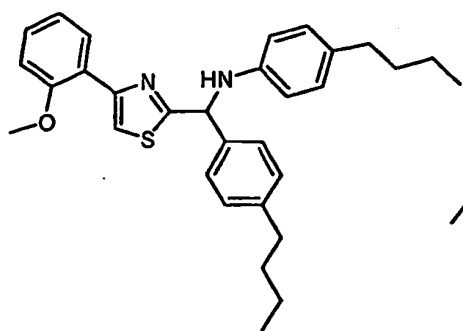
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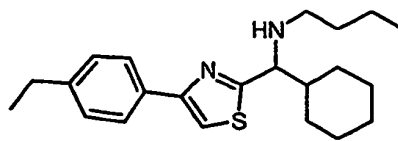
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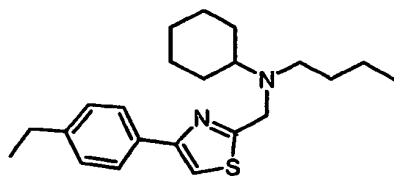
Fig. 1



B1

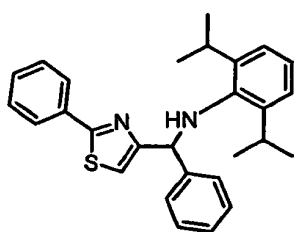


B2

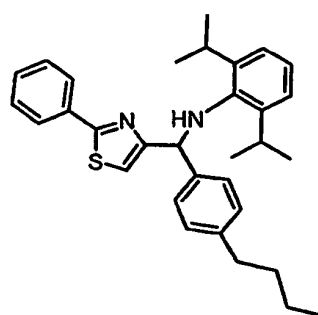


B3

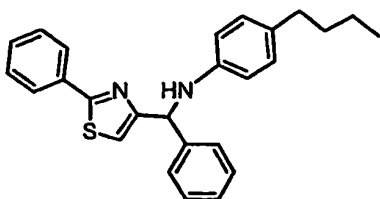
Fig. 2



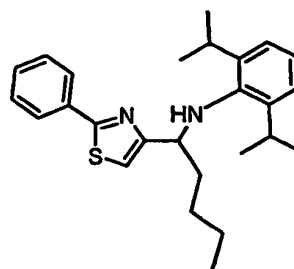
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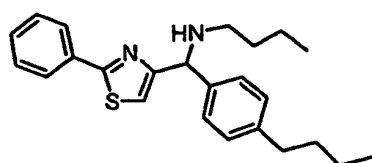
C2



C3



C4



C5

Fig. 3

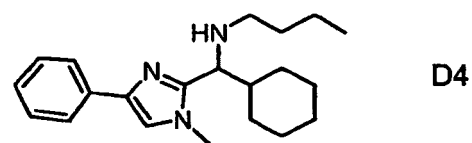
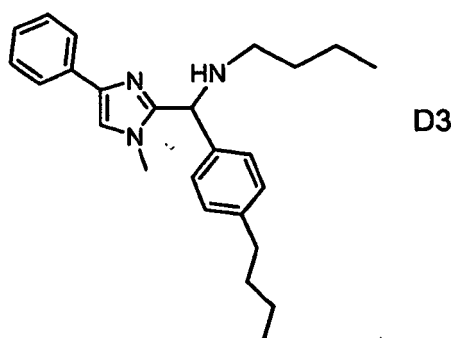
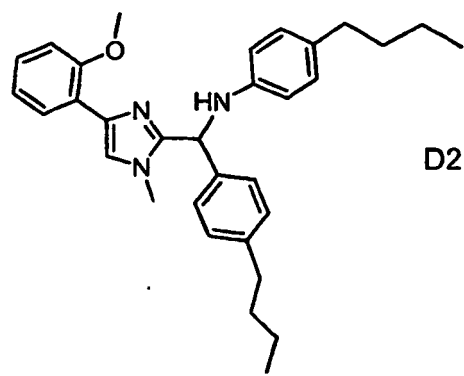
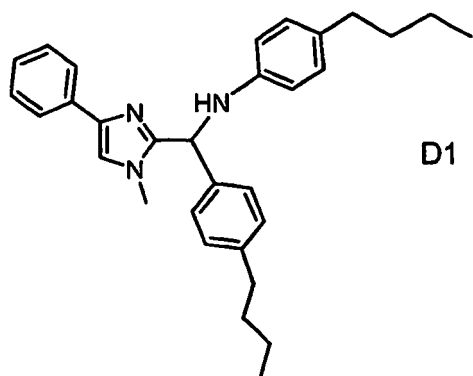
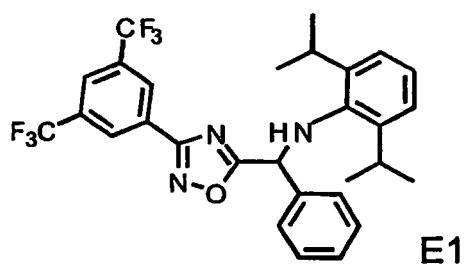


Fig. 4



REFERENCES CITED IN THE DESCRIPTION

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